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STUDY OF THE COSTS AND BENEFITS OF COMPOSITE MATERIALS IN ADVANCED TURBOFAN ENGINES

by

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GENERAL ELECTRIC COMPANY
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16. Abstract

This program developed composite component designs for a number of applicable engine parts and functions. The cost and weight of each detail component was determined and its effect on the total engine cost to the aircraft manufacturer was ascertained. The economic benefits of engine or nacelle composite or eutectic turbine alloy substitutions was then calculated.

Two time periods of engine certification were considered for this investigation, namely 1979 and 1985. Two methods of applying composites to these engines were employed. The first method just considered replacing an existing metal part with a composite part with no other change to the engine. The other method involved major engine redesign so that more efficient composite designs could be employed.

Utilization of polymeric composites wherever payoffs were available indicated that a total improvement in DOC of 2.82 to 4.64 percent, depending on the engine considered, could be attained. In addition, the percent fuel saving ranged from 1.91 to 3.53 percent. The advantages of using advanced materials in the turbine are more difficult to quantify but could go as high as an improvement in DOC of 2.33 percent and a fuel savings of 2.62 percent. Typically, based on a fleet of one hundred aircraft, a percent savings in DOC represents a savings of four million dollars per year and a percent of fuel savings equals 23000 m^3 (7,000,000 gallons) per year.

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FOREWORD

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1.0 SUMMARY

This report presents the results of a program for the "Study of the Costs and Benefits of Composite Materials in Advanced Turbofan Engines." This program had as its objective the evaluation of the effects of applying composite materials to advanced turbofan engines. This evaluation included the determination of the potential weight and production costs of individual components compared to equivalent metal structures, an estimation of the development costs required to realize these weight and cost projections, and an estimate of the potential payoffs based on total life cycle costs. These payoffs were determined by evaluating the direct operating cost (DOC), return on investment (ROI), and fuel used for given sized fleets.

Two time periods of engine certification were considered for this investigation, namely 1979 and 1985. Two methods of applying composites to these engines were employed. The first method just considered replacing an existing metal part with a composite part with no other change to the engine. The other method involved major engine redesign so that more efficient composite designs could be employed. The levels of technology employed assumed that those concepts which already had attained some proof-of-concept through existing or recent R&D programs would be available for the 1979 engines, while some of the more advanced paper concepts as well as some material improvements would be available for the 1985 engines. The engine technology employed was essentially that used for the Advanced Transport Technology studies. From an acoustical standpoint, the 1979 engine designs were configured to meet FAR36 minus 10 EPNdb while the 1985 engines were designed for the FAR36 minus 15 EPNdb.

This program developed composite component designs for a number of applicable engine parts and functions. The cost of each detail component was determined and its effect on the total engine cost to the aircraft manufacturer was ascertained. This was done through a standard type business plan engine pricing analysis. The input to this analysis consisted of shop costs, development costs and tooling costs. The economic benefits of engine or nacelle composite or eutectic turbine alloy substitutions was then calculated by converting the resulting weight, cost and performance engine changes into changes in the base aircraft characteristics. Trade factors for specific changes in engine parameters were then calculated holding payload and range constant and allowing the gross weight to vary as required.

Composite material substitutions were made with no effect on engine SFC (cost and weight changes only). Eutectic turbine alloy and tungsten wire/superalloy composite substitutions, however, result in cooling flow reductions which result in SFC and engine core size changes for constant thrust.

In determining aircraft economics, Direct Operating Costs (DOC's), were found using 1967 ATA formula (ref. 4) modified by General Electric. These changes are to engine material and labor costs only, reflecting GE's experience. This method and modifications were approved by NASA for use during the ATT engine study contract. Deviations from ATT approved procedures were an increase in fuel price to 25 cents/gallon, reflecting present conditions, and a labor rate of $6.50 per hour. All other items are unchanged from those used in the ATT Contract Study. Indirect Operating Costs (IOC's) were found using Lockheed Georgia Report Number LW70-500R dated May 1970. Again this was approved for use for ATT contracts by NASA. Return on Investment (ROI) was calculated using the DOC's and IOC's as determined above, a 48% tax rate, and discounting the resulting stream of cash flow.

Utilization of polymeric composites wherever payoffs were available indicated that a total improvement in DOC of 2.82 to 4.64 percent, depending on the engine considered, could be attained. In addition, the percent fuel saving ranges from 1.91 to 3.53 percent. The advantages of using advanced materials in the turbine are more difficult to quantify but could go as high as an improvement in DOC of 2.33 percent and a fuel savings of 2.62 percent. Typically, based on a fleet of one hundred aircraft, a percent savings in DOC represents a savings of four million dollars per year and a percent of fuel savings equals 23000 m^3 (7,000,000 gallons) per year.

It is apparent that very significant cost and weight savings can be obtained by the use of composite materials in turbofan engines. The areas where these benefits appear to be the greatest are in the engine nacelle, fan frame, and fan blades in the cooler portion of the engine and in turbine blades.

2.0 INTRODUCTION

With the emergence and subsequent development of advanced composites during the last ten years, a highly promising new family of materials is now available for consideration in aircraft engine applications.

Initial evaluations and applications have indicated that impressive savings in both weight and cost can be obtained in a significant portion of typical turbofan engine components through the use of these materials.

Most of this previous effort on advanced composites has been directed at specific components of existing engines with the objective of reducing the weight of the component as much as possible. Payoff analysis has, for the most part, been limited to the effect that these components have, individually, on engine performance with cost being of secondary importance.

On the other hand, the application of fiberglass composites to engine structure has emphasized the cost aspects as well as weight savings.

In both cases, however, most of this work has been done based on existing engines or engine designs and the composite designs were essentially constrained to material substitution applications. In those cases where the composite design has varied from standard metal design, the overall part size was not changed and no resizing of the engine attempted.

It was the overall purpose of this program to correlate all of the component experience and conduct a comprehensive study of an advanced turbofan engine that can be modified or resized to take maximum advantage of the potential of composite materials. This study not only considered the criteria of lower weight and improved performance of both the engine and an assumed aircraft, but placed primary emphasis on the full spectrum of costs associated with the development, fabrication, testing, and service life of such an engine, culminating in an overall evaluation of the materials to new generations of civil aircraft systems.

3.0 DISCUSSION

The basic objective of this program was to evaluate the effects of applying composite materials to advanced turbofan engines. This evaluation included the determination of the potential weight and production costs of individual components compared to equivalent metal structures, an estimation of the development costs required to realize these weight and cost projections, and an estimate of the potential payoffs based on total life cycle costs. These payoffs were determined by evaluating the direct operating cost (DOC), return on investment (ROI), and fuel used for given sized fleets.

Two time periods of engine certification were considered for this investigation, namely 1979 and 1985. Two methods of applying composites to these engines were employed. The first method just considered replacing an existing metal part with a composite part with no other change to the engine. The other method involved major engine redesign so that more efficient composite designs could be employed. The levels of technology employed assumed that those concepts which already had attained some proof-of-concept through existing or recently completed R&D programs would be available for the 1979 engines while some of the more advanced paper concepts as well as some material improvements would be available for the 1985 engines. The engine technology employed was essentially that used for the ATT studies. From an acoustical standpoint, the 1979 engine designs were configured to meet FAR36 minus 10 EPNdb while the 1985 engines were designed for the FAR36 minus 15 EPNdb.

The approach taken to achieve the program objectives, the basis of comparison, and the program results are presented in the following paragraphs.

3.1 BASELINE DEFINITIONS

This section defines the aircraft and engine configurations which were used as the basis for the cost and benefit analysis.

3.1.1 Baseline Aircraft

A typical Advanced Technology Transport aircraft designed for 0.9 Mach number was used as a basis for this study. This trijet with supercritical aerodynamic technology is similar to other aircraft studied and reported on under previous NASA contracts.

The fuselage has a conventional constant cross section of 5.5 m (18 ft) in diameter; sized for seven abreast coach seating and standard cargo bay containers. The wings have a mid-chord sweep of 0.628 radians (36 degrees). Current aluminum construction is used in the aircraft which is sized for a payload of 18143 kilograms (40,000 pounds) or 195 passengers over a maximum range of 5556 kilometers (3000 nautical miles) at a design cruise speed equivalent to 0.9 Mach number.

3.1.2 Baseline Engines

The engines selected for this study were a current technology engine and two advanced engines which were evolutions of the ATT engines described in Reference 1. The design characteristics of these engines are compared in Table I. The changes made in the ATT engines are associated with the change in cruise Mach number from the 0.95 - 0.98 level emphasized in Reference 1 to the 0.9 level of the current study. In addition, the fan aerodynamic characteristics were made consistent with the ATT 1.8 pressure ratio fan now in development under contract to NASA.

The installations of the various engines were designed to meet the noise objectives for the current study. The configurations are summarized in Table II and illustrated on Figures 1 through 4. Installation #1 (Figure 1) is the current technology engine in its production nacelle which meets current FAR requirements with considerable margin. Installation #2 (Figure 2) is a modification of the above to meet FAR-10. Installation #3 (Figure 3) is the 1979 certification engine with a long duct nacelle to meet FAR-10. Installation #4 (Figure 4) is the 1985 certification engine with a nacelle defined to meet FAR-15. Alternate inlet approaches, fixed geometry with splitters or variable geometry are possible as shown in Figure 4. Installation #4 requires a two position nozzle to meet the noise requirement (not shown on drawings).

The aircraft characteristics used in the noise evaluation are summarized in Table III. These are the same characteristics used in an ATT follow-on study conducted by GE under contract to NASA (Reference 2).

The results of the acoustical evaluation for the specified flight conditions and power settings are summarized on Table IV. The noise level relative to the FAR 36 level (shown at the bottom of the Table) is tabulated at the three measuring points. The traded values are shown in the right hand column. The composite designs in this study were carried out for the 1979 and 1985 engines in a manner which held noise at the objective levels.

Table I. Basic Engine Definitions.

	Current Technology	1979 Engine	1985 Engine
Cruise Cycle Conditions			
Bypass Ratio	4.2	4.5	7.0
Overall Pressure Ratio	31	30	36
T_4 - Std. + 10°C day	1132°C (2070°F)	1260°C (2300°F)	1427°C (2600°F)
Takeoff			
T_4 - Std. + 15°C day	1277°C (2330°F)	1371°C (2500°F)	1538°C (2800°F)
Fan (Cruise)			
Pressure Ratio	1.72	1.75*	1.75*
$\frac{W\sqrt{\theta}}{\delta A}$ kg/sec-m^2 (lb/sec-ft^2)	210 (43)	210 (43)	210 (43)
$U_T/\sqrt{\theta}$ m/sec (ft/sec)	442 (1450)	488 (1600	488 (1600)
Inlet Radius Ratio	.375	.38	.38

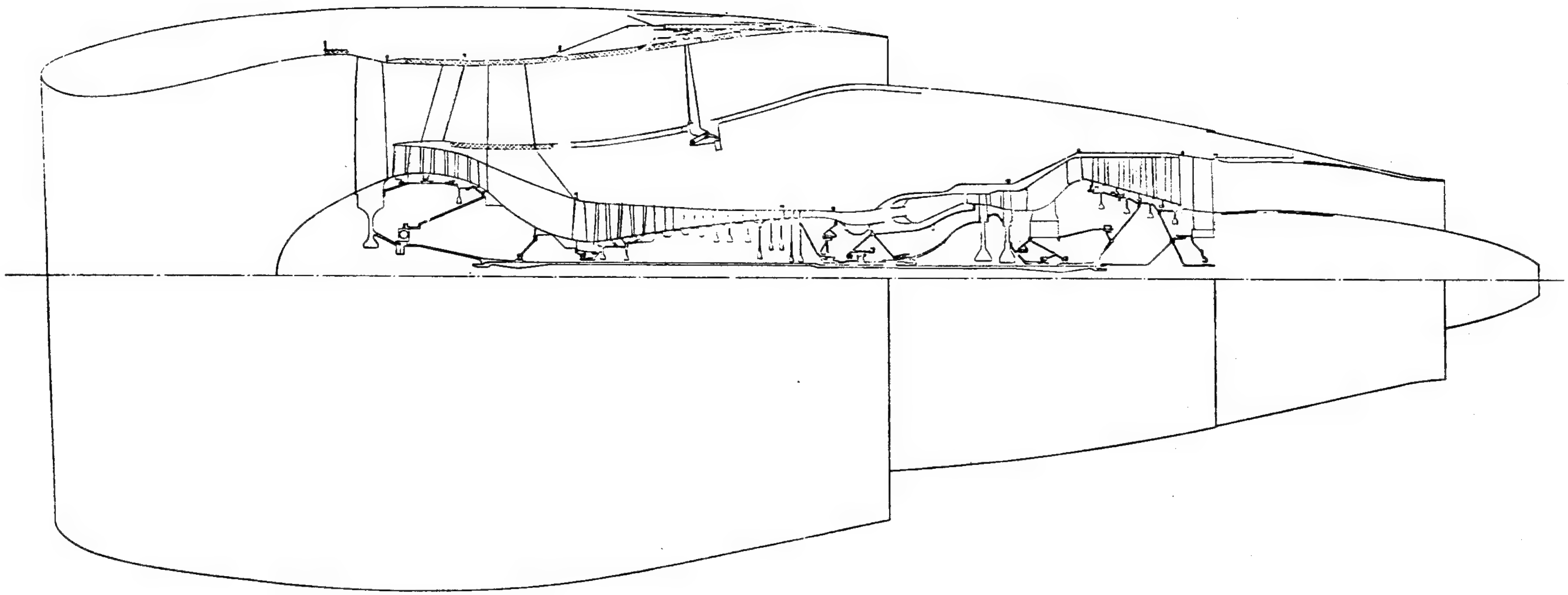
* Uses ATT 1.8 P/P fan with design pt. @ Max. Climb.

Table I. Basic Engine Definitions (Concluded).

	Current Technology	1979 Engine	1985 Engine
Boosters			
# Stages	3	2	2
Des. Pressure Ratio (incl. Fan Hub)	2.40	2.5	2.75
Core Compressor			
# Stages	14	9	9
Des. Pressure Ratio	13.0	12.0	14
$U_T/\sqrt{\theta}$ m/sec (ft/sec)	341 (1120)	410 (1345)	427 (1400)
Inlet Radius Ratio	0.48	0.7	0.68
Combustor			
Type	Annular Atomizing	Annular Carbureting	Double Annular
Core Turbine			
# Stages	2	1	1
LP Turbine			
# Stages	4	3	4 1/2
Ψ_P Ave.	0.95	1.1	1.7
Exhaust			
Type	Separate	Mixed	Mixed
Variable Area	No	No	Yes

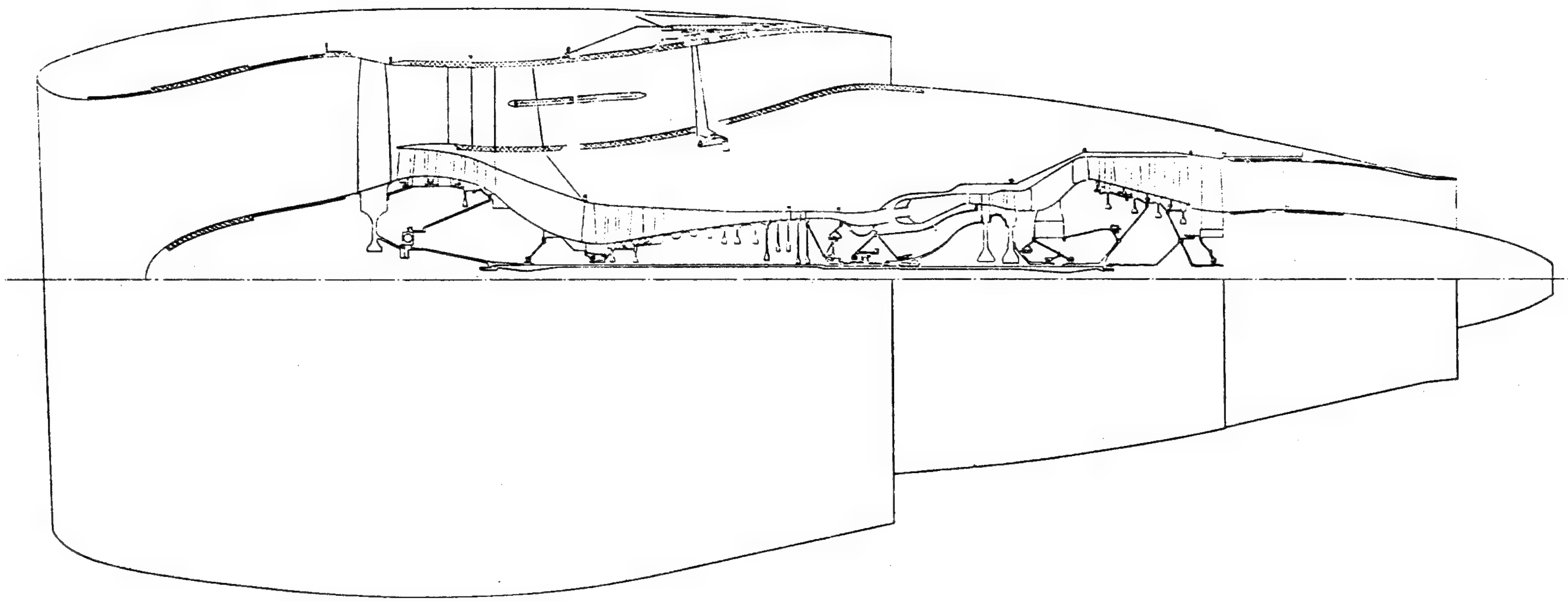
Table II. Acoustic Configurations.

Installation	Feature
#1 - Current Technology - Production Nacelle	• Inlet Wall Treatment • Separate Flow Exhaust • Exhaust Wall Treatment
#2 - Current Technology - Modified Nacelle (Same Aero Lines as #1)	• Respaced Rotor/OGV and IGV • Treated Inlet Spinner • Exhaust Splitter • Additional Exhaust Treatment
#3 - 1979 Engine - Long Duct Mixed Flow	• Extended Inlet and Wall Exhaust Treatment • Treated Inlet Spinner • Fixed Geometry
#4 - 1985 Engine - Based on ATT Follow-On Study	• Baseline Two Splitter Inlet • Alternate V.G. "Hybrid" Inlet • Fan Exhaust Splitter • Two Position Jet Nozzle



Short Cowl/Separated Flow
FAR 36 - 5 EPN db
- Wall Treatment

Figure 1. Engine #1 Current Technology.



Short Cowl/Separated Flow
FAR 36 - 10 EPN db

- Treated Spinner
- Exhaust Splitter
- Respaced Fan/OGV
- Turbine Exhaust Treatment

Figure 2. Engine #2 Current Technology.

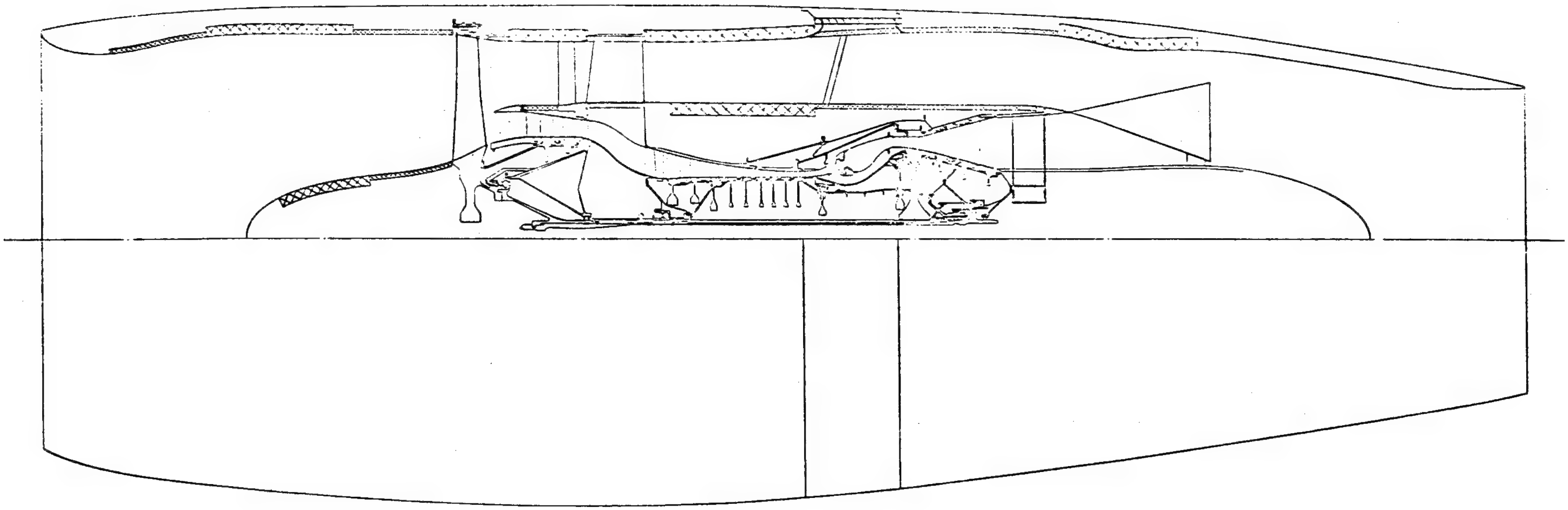
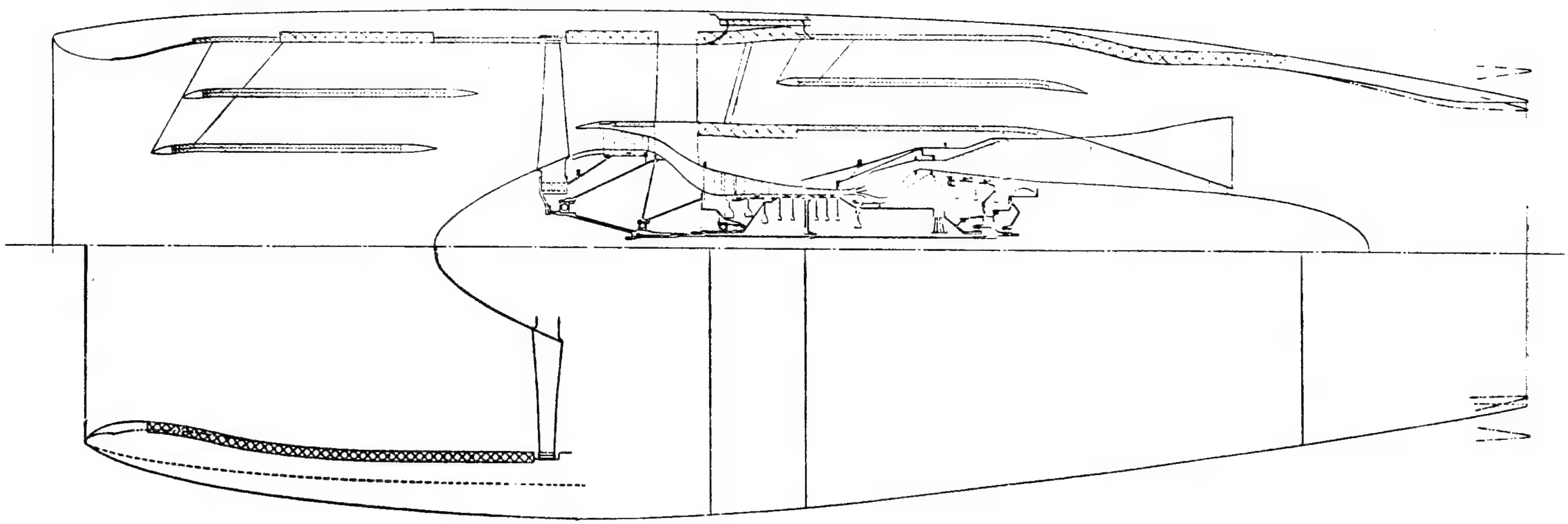


Figure 3. Engine #3 1979 Certification.



Long Duct/Mixed Flow
FAR 36 - 15 EPN db

- Variable Geometry Inlet Versus Fixed Inlet and 2 Splitters
- Exhaust Splitter
- Two Position Exhaust Nozzles

Figure 4. Engine #4 1985 Certification.

Table III. Airplane Requirements Used for Acoustical Estimates.

Condition	Altitude	Mach No.	Thrust N (lb) 767-640	% Takeoff Thrust at Specified Flight Condition
Engine Sizing	304.8 m (1000 ft.)	0.16	111,206 (25,000)	100%
Approach .052 r (3^o) Glide Slope	Sea Level	0.22	28,380 (6380)	26%
Takeoff (Noise)				
No Cutback	411.5 m (1350 ft.)	~0.22	106,757 (24,000)	100%
With Cutback	390.1 m (1280 ft.)	~0.22	84,961 (19,100)	80%

Trijet (2 wing, 1 tail mounted); 18,144 kg (40,000 lb.) payload; 5,556 km (3,000 n. mile) range; Design Cruise Mach No. = 0.90.

Table IV. Noise Levels, Relative to FAR Requirements.

Installation	Takeoff Community	Approach	Side Line	Traded
#1 - Current Technology	-6 (-4 W/O cutback)	-5	-12	-7 (-6 W/O cutback)
#2 - Current Technology	-9 1/2	-9	-16	-10 1/2
#3 - 1979 Engine	-8 1/2	-11 1/2	-11	-10
#4 - 1985 Engine				
Baseline FG Inlet	-13	-16 1/2	-16	-15
VG Inlet	-14	-14 1/2	-17	-15
FAR 36 Requirement EPNdB	103	106	106	

3.2 MATERIALS

The composite materials which were considered for application to the study effort, along with their projected costs in the appropriate time period, are shown below.

	Cost Per Pound	
	1979 Engine	1985 Engine
Graphite/Epoxy	$ 30	$ 10
Graphite/Polyimide	35	12
Boron/Epoxy	90	30
Boron/Aluminum	100	30
Boron/Titanium	200	50

Both an advanced NiTaC eutectic alloy and a tungsten wire Super alloy composite were considered for high temperature applications but no specific costs were assumed. Data is given in Section 3.6 for the components utilizing these materials which cover a range of costs.

A number of other types of composite materials exist but it was felt that either they had too little potential compared to those listed or their developmental stage and/or data availability did not warrant their inclusion at this time in this type of study.

3.3 COMPONENT DESIGNS

This section discusses the various composite component designs that were generated to evaluate the weight and cost benefits that could be achieved through the application of composites to high bypass turbofan engines. The designs shown herein are representative designs based on experience gained through various research programs which have been conducted in the past and are not the result of detailed optimization studies. It is felt however that these designs are totally adequate to demonstrate the payoff potential of composite application even though the details of an actual hardware design may differ in some instances.

For each component, design concepts were considered for both a part replacement version (no change to other attaching structures) and a redesign version (other engine components changed to accommodate a more efficient composite design). In some cases these designs were not significantly different and in others there were major changes. Also, in some cases such as fan blades, it was not considered practical to use a straight replacement concept.

In order to provide a basis of comparison for the composite components, the baseline engines, as defined in Section 3.1.2, were used. All engines and components were scaled to the same thrust size to provide a realistic comparison.

3.3.1 Engine Static Structure

Design concepts for all of the engine major static structure components are shown in Figures 5 through 9. These figures contain views of the entire component plus detailed views of any regions thought to be necessary in establishing the fabrication complexity, the strength integrity, the part cost, the component weight, and the structures' reliability and maintainability.

The 1979 bypass stator case, 1979 fan frame, and the 1985 vane/frame are designed using the same structural design concept. This concept consists of a method of constructing a component by using integral wheel-like structures joined together by relatively light shear panels which form the flowpaths. The structure is then locally reinforced in the rim and hub areas as needed. This concept results in a structure which is capable of carrying high loads but which is easy to fabricate and requires a minimum amount of tooling.

Since the frames and stator cases are inherently complex and highly loaded structures, a multiplicity of high-strength joint concepts are required to satisfy load transfer requirements. This design concept not only satisfies the requirement of high structural integrity but also yields significant payoff in both cost and weight when compared to conventional, metallic mechanical constructions.

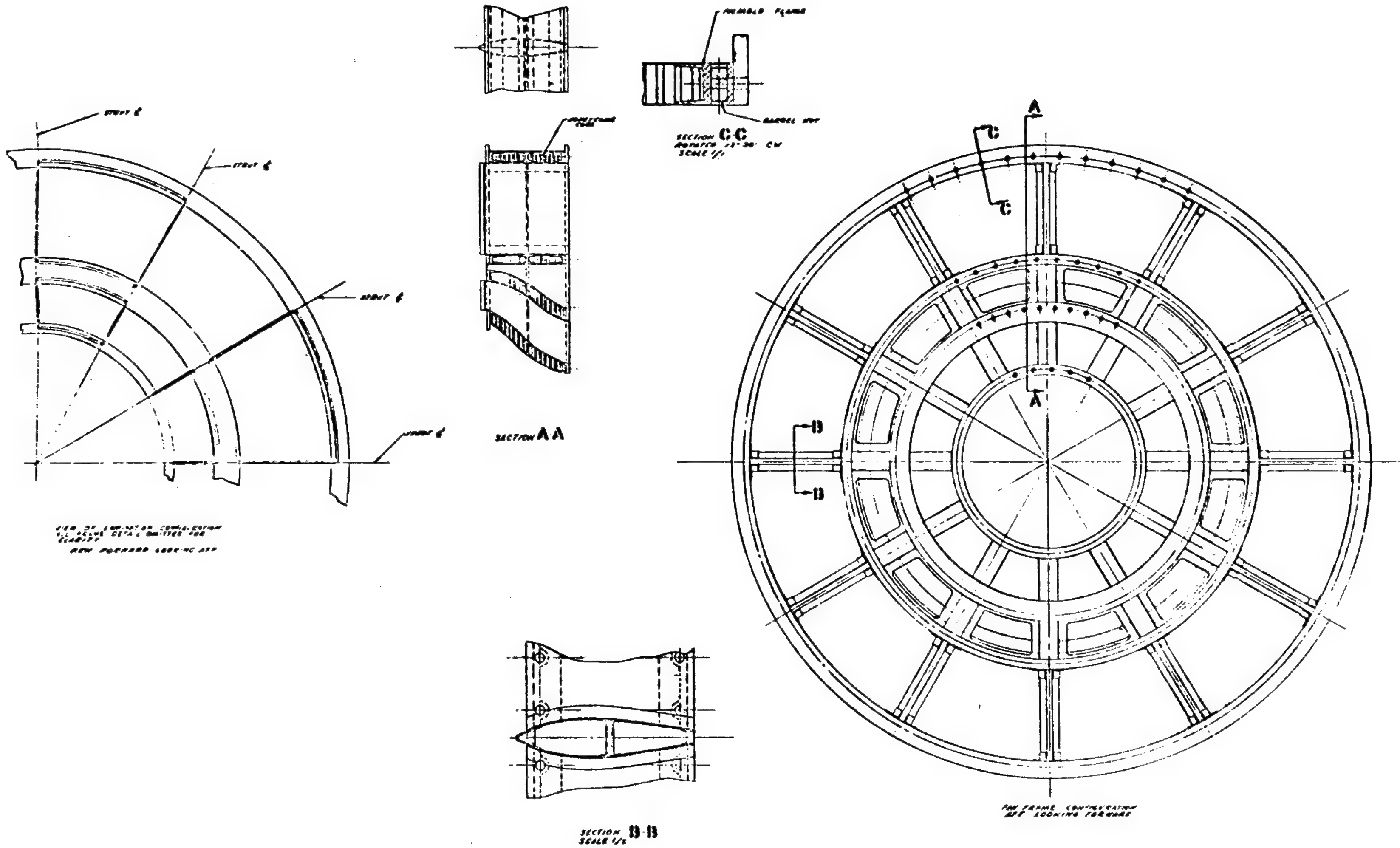


Figure 5. 1979 Composite Replacement Fan Frame.

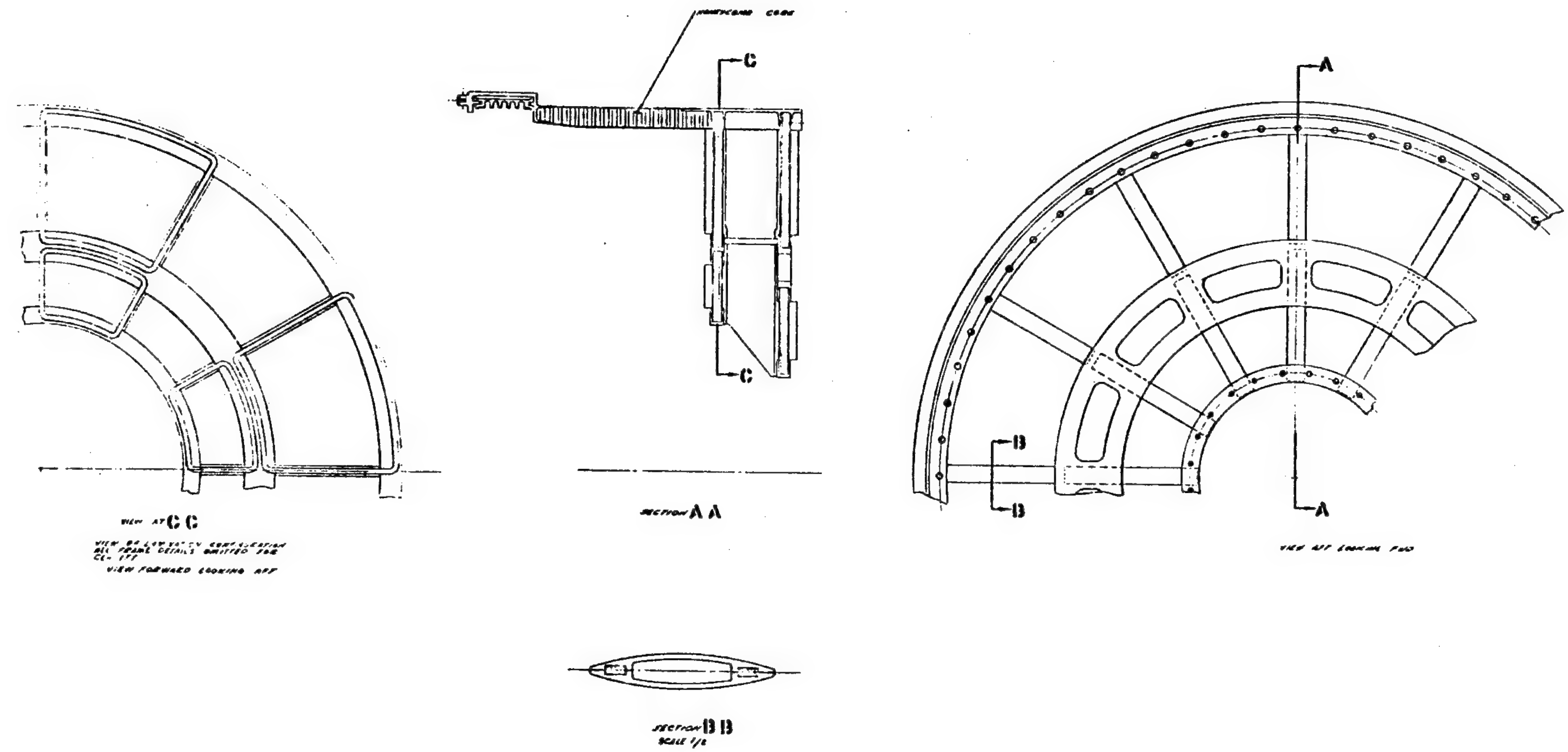


Figure 6. Composite Redesign Fan Frame.

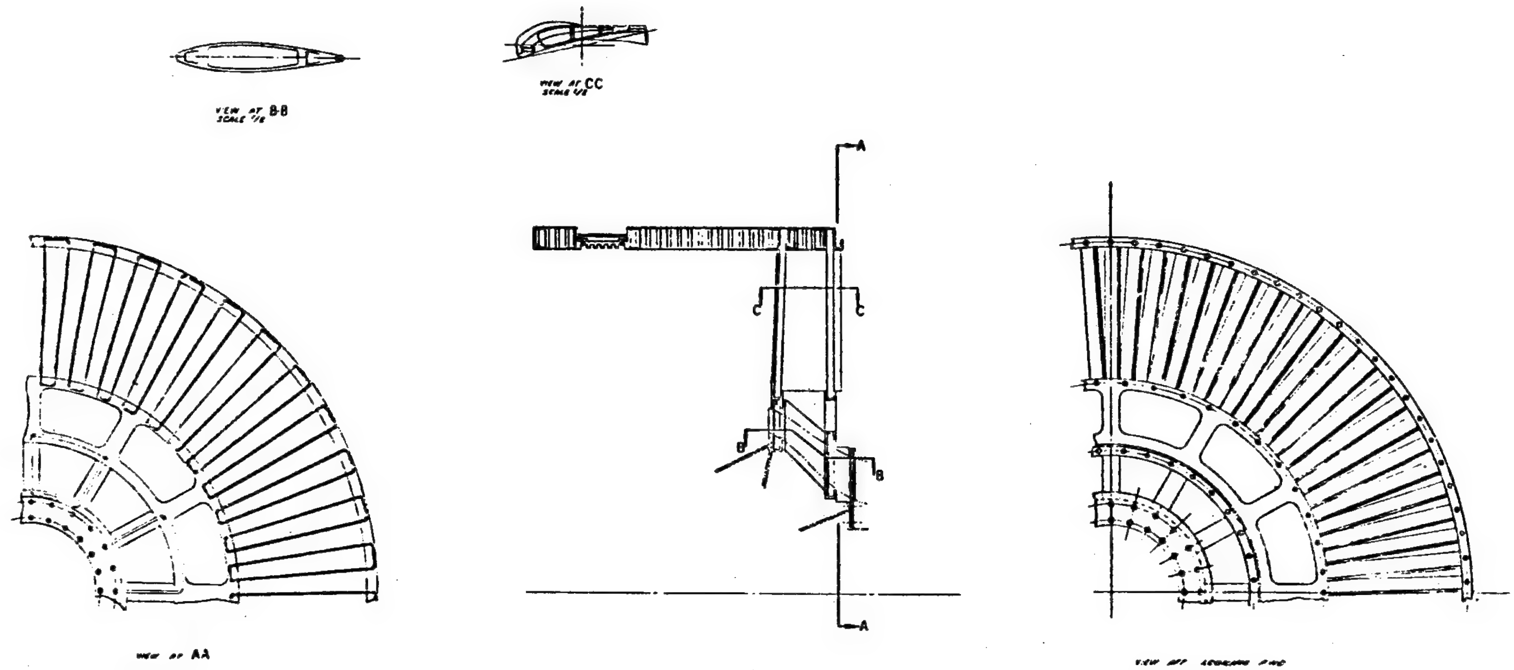


Figure 7. 1985 Composite Vane/Frame.

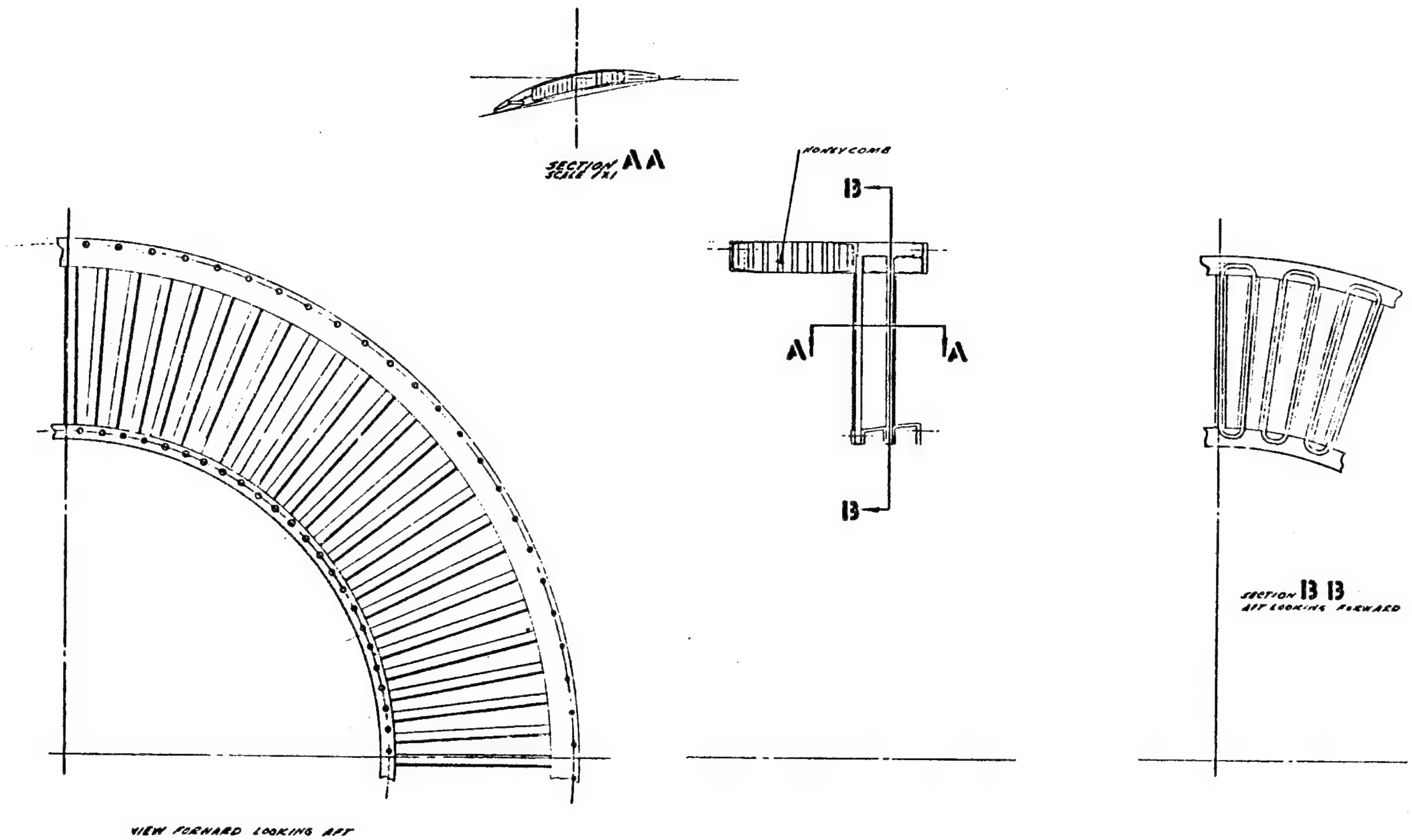


Figure 8. 1979 Bypass Stator Case (Replacement).

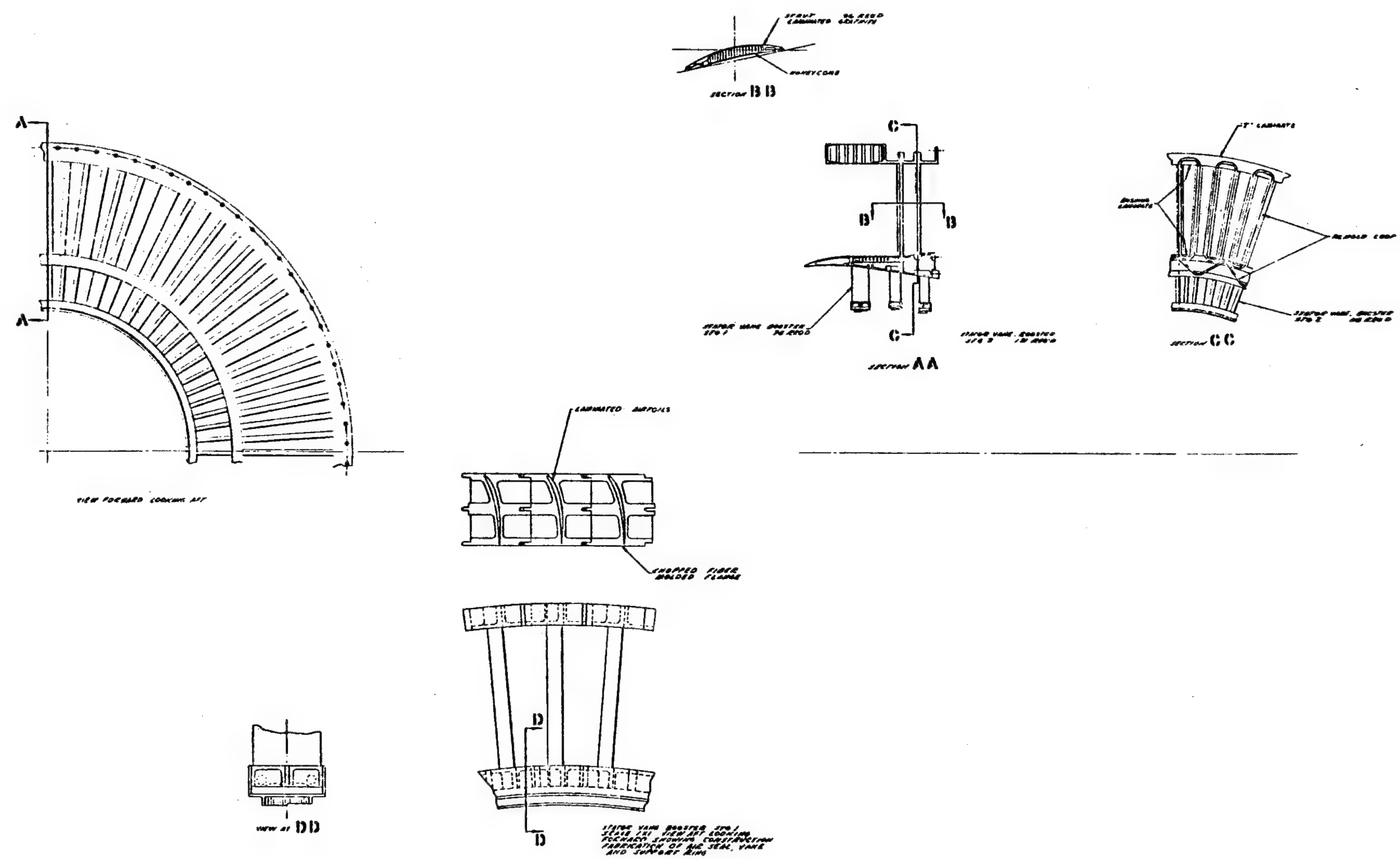


Figure 9. Booster and Bypass Stator Case.

In essence, the overall structural concept to be used for the proposed frames consists of three basic elements (i.e., structural "wheels," shear panels, and flanges), with each element designed to perform a specific load-carrying function. A perspective of a typical composite fan frame is illustrated in Figure 10.

The most vital parts of the frame are the structural "wheels." The structural "wheels" contain five basic parts as shown in Figure 11. The first part is a loop of continuous fibers which form a portion of the strut and ring structures. The second and third parts are graphite/resin laminated bushings located in the outer and inner rings, and serve as the primary load members in transferring radial tensile loads out of the strut and into the rings. The fourth and fifth parts are graphite/resin laminated "T" members located in the outer and inner rings, and serve as the primary load members in transferring radial compressive loads and ring loads from one strut to another. The shear panels and flanges are composite laminate parts.

Figure 5 depicts the 1979 composite replacement fan frame for the 1979 engine. Figure 5 also depicts a vertical cross-sectional view of one of the "wheel" components. As seen in the figure, the inner ring of the bypass strut "wheel" and the outer ring of the core strut "wheel" are connected together. This connection is formed by modifying the shape of the laminate "T" members to accompany both the inner and outer continuous fiber loops. These modified "T" members would also contain large "lightening" holes to reduce "wheel" weight and to provide access to the inner faces of the splitter flanges.

The shear panels are bonded to the four sides of each "wheel" cavity and serve as the basic load-carrying members between "wheels." The panels perform the following functions. First, they transfer shear forces between wheels imposed on the frame by a forward overturning bending moment. Second, they transfer radial tensile and compressive forces between casings imposed on the struts by a tangential bending moment. Third, they transfer axial tensile and compressive forces between "wheels." Fourth, they serve as the airflow surfaces within the frame cavities. Fifth, they serve as a part of the acoustic sound-suppression structure. All flowpath shear panels are sandwich structures with the bypass panels containing an acoustical core and the core panels containing conventional honeycomb material. Laminate "U" flanges bonded to both skins of the sandwich panel structures provide for the attachment of the panels of each sandwich structure to the inner, middle, and outer ring of each "wheel" component.

Figure 6 illustrates the 1979 composite fan frame for the 1979 composite redesign version. As seen in the figure, the major design difference between it and the replacement version is the elimination of one of the "wheels." This elimination is

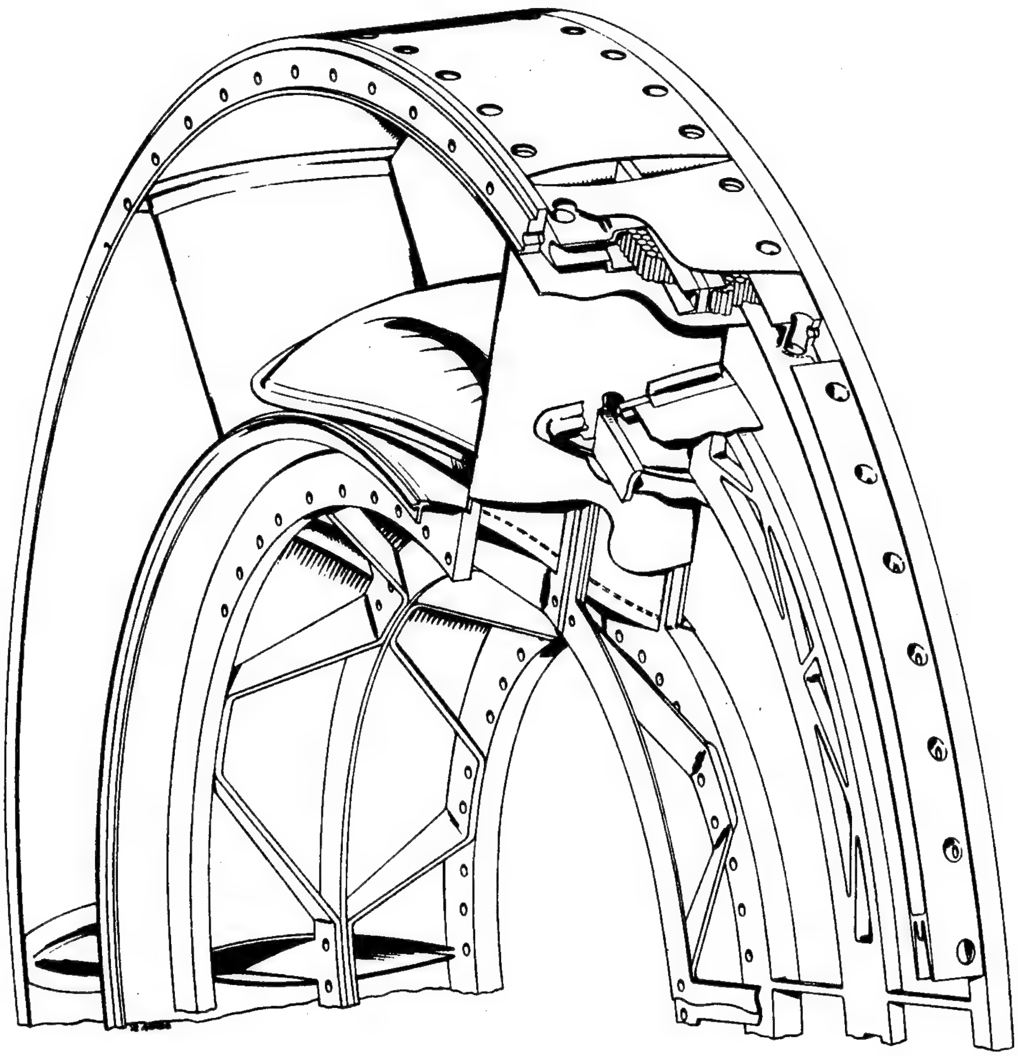


Figure 10. Typical Composite Fan Frame Trimetric.

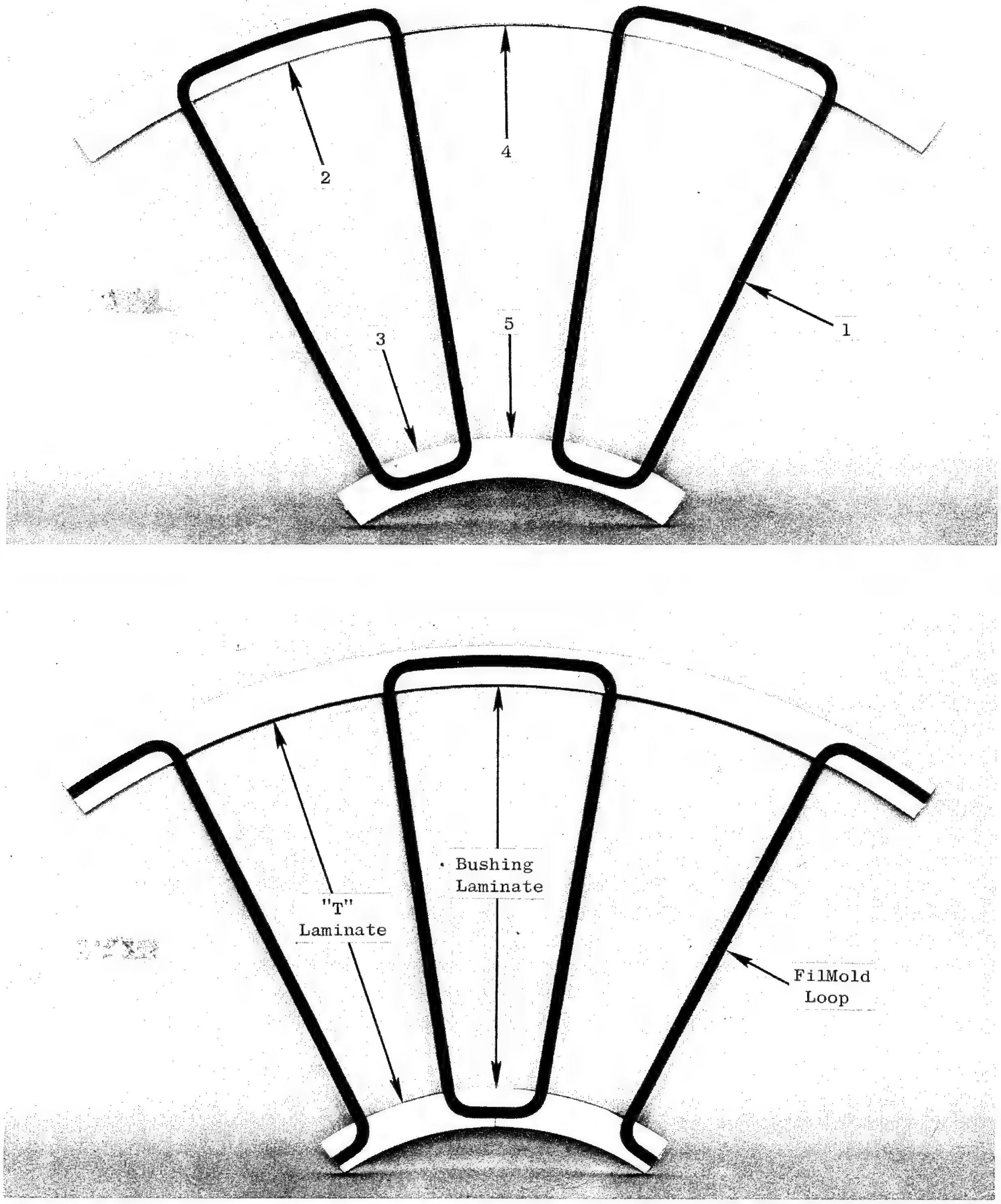


Figure 11. Integrated FilMold "Wheel" Construction.

possible due to the redesign of the various interface geometries. In the 1979 composite replacement fan frame, the flanges occur at the extreme ends of the frame. This geometry causes the spokes of the fore and aft "wheels" to be relatively small, therefore, a middle "wheel" is required to carry a portion of the loads. Relocating the fore and aft "wheels" towards the center of each strut allows for the enlargement of the spokes, the elimination of the middle "wheel," and therefore, a large reduction in the frame weight.

The 1985 composite frame structure is shown in Figure 7. This structure is a combination of a fan frame and a bypass stator vane assembly, therefore, the structure is termed a vane/frame. The 1985 vane/frame is similar in construction to the 1979 composite fan frame (redesign version). The basic difference is that the number of struts in the bypass region is increased to reflect the number of stator vanes required for the engine. This configuration is shown in view A-A of Figure 7.

There are two basic differences between the replacement and redesign versions of the 1985 vane/frame. The first change is the elimination of the forward frame flange in the region of the strut leading edge. The second change is the design method used in providing stiffness to the struts and vanes. In the replacement version the spokes are required to provide the general stiffness of the frame. Geometrical restrictions caused by accessory hardware and tubing prevent the strut and vane skins from providing excessive stiffness. In the composite redesign version of the vane/frame the relocation and redesign of hardware permits the skins to provide a larger portion of the frame stiffness. Both of the above mentioned changes permit the composite redesign version of the 1985 vane/frame to be considerably lighter than the replacement version.

The design of the 1979 bypass stator case is shown in Figure 8. The design concept utilized for this structure is the "wheel"/shear panel concept; this is the same design philosophy used in the frame design. The outer rings of the two "wheels" are bonded to the composite flanges which provide the interface for the frame and nacelle.

The booster stator case, shown in Figure 9, is similar in shape and function to the bypass stator case, but since the loading condition of the booster stator case is lower than the bypass stator case, the design concept is different. The booster stator case consists of solid airfoils, transition joints, and rings. Transition joints formed from chopped fiber, molding compound are simultaneously molded around both ends of a pre-molded laminate airfoil. These vane elements are then clustered together and bonded to the faces of four premolded laminate ring structures. The resulting structure is a complete single stage, stator case assembly. The various stages are connected with laminate "U" shaped channels which are bonded to the exterior, inner and outer ring structures. The "U" shaped channels also form the inner and outer flowpath panels.

The weight breakdown for the various composite static structure components investigated in the program and listed and described above are listed in Table V.

3.3.2 Nacelle Structure

Due to the stringent noise requirements of both the 1979 and 1985 engines studied during this program, extensive acoustic treatment is required on the outer bypass duct. Therefore for the purposes of this discussion, this structure will be considered in the same light as the nacelle and will be constructed in the same manner. The containment weight is shown as part of the total nacelle weight but will be discussed under fan blades.

On aircraft in service today, the nacelle part of the propulsion system installation is a completely separate structure that accounts for 25-35 percent of the overall system weight. To date, advancement in nacelle technology has not kept pace with advanced technology engine weight reductions. Acoustic panels which are now part of the nacelle system have been added, independent of the nacelle structure.

The 1979 certification propulsion system takes an initial step forward in nacelle design by integrating the acoustic panels into the nacelle structure load path. The basic construction is similar to the typical sheet metal-bulkhead-stringer design, except they will utilize composite materials. The inner and outer flowpath shells would be fabricated from composite laminates. In regions where the nacelle shell depth is small, the core material will be conventional honeycomb. In regions where the nacelle shell depth is large, the two shells would be attached together through the use of composite laminate "wheels" which would form bulkheads within the nacelle. In regions where acoustic treatment is necessary the acoustic structure would be provided by structural acoustic panels mechanically fastened to the inner flowpath shell of the nacelle.

In the 1985 certification propulsion system,further integration of the engine and nacelle structure is anticipated. With the more stringent noise requirements, higher inlet Mach numbers have evolved, reducing inlet area and with approximately the same inlet throat to highlight diameter ratio and increased highlight to nacelle maximum diameter ratio. The engine-to-nacelle flowpath thickness can then be reduced from approximately ten inches on the DC10-30/CF6-50 installation to as low as three inches. With this large reduction in cross section the fan cowl and casing can now be integrated into one assembly thus eliminating one component from the nacelle parts list. The bolt-in acoustic panels of the 1979 design are now an integral part bonded into the nacelle structure. The inlet core (internal to external flowpath) will be of honeycomb construction, the inner cells/resonators sized by acoustic requirements. A close-out sheet will separate this noise suppression/nacelle structure from the honeycomb to the outer face sheet or nacelle external flowpath. This type of construction is used throughout the nacelle.

Table V. Weight Breakdown of Composite Static Structures, kilograms (pounds).

Component	1979		1985	
	Replacement	Redesign	Replacement	Redesign
Frame				
• Mounts	15 (33)	15 (33)	21 (46)	21 (46)
• Bearing Cones	27 (60)	27 (60)	21 (47)	21 (47)
• Basic Frame	135 (297)	118 (260)	212 (467)	190 (420)
Booster Stator Case				
• First Stage Booster Stator	3 (7)	3 (7)	3 (7)	3 (7)
• Second Stage Booster Stator	2 (4)	2 (4)	2 (4)	2 (4)
• Third Stage Booster Stator	1.4 (3)	1.4 (3)	1.4 (3)	1.4 (3)
• Inner Core Shrouds	7 (16)	7 (16)	5 (11)	5 (11)
• Forward Splitter Portion	10 (22)	10 (22)	7 (15)	7 (15)
• Outer Core Shell	18 (40)	18 (40)	16 (35)	16 (35)
• Inner Bypass Shell	38 (84)	29 (65)	23 (50)	23 (50)
Bypass Stator Case				
• Outer Casing	73 (160)	68 (150)	N/A	N/A
• OGV	27 (60)	27 (60)	N/A	N/A

All duct structures shown in the 1979 and 1985 engine cross sections are sandwich structures with composite, "U" shaped flanges bonded to the ends of both shells. The duct flanges are fastened to adjoining structures through the use of barrel nuts located in radial pockets molded in the composite flange. The core structure bonded to the inner and outer composite laminate shells is either a conventional honeycomb core or a molded acoustic core, depending on the acoustic noise requirements which dictate the core material to be utilized.

Maximum reduction in nacelle cross sectional area is obtained by mounting engine/aircraft accessories on top of the engine. Engine cross sections shown in Figures 12, 13, and 14, however, show the more conventional arrangement and bulge in the nacelle flow lines with the accessories mounted at the bottom of the engine on the fan case. Required piping and wires get to the gearbox in the slot formed by the fan frame rings and internal flowpath and from the gearbox to engine through the bottom pylon. With the top mounted accessories the bottom pylon is eliminated and all service lines go through the top pylon. The top pylon is required in either gearbox arrangements for propulsion system mounting structure.

A translating cowl, cascade type fan flow reverser is shown on both the engines. Blocker actuator arms extend across the flowpath which requires "bi-furcated" duct doors similar to the DC10-30/CF6-50 installation. Door assemblies will be mounted to the pylon and opened for easy access to the engine and aircraft/engine systems.

The weight breakdown of the above mentioned composite structures is listed in Table VI.

The spinner of the engine is designed to provide an aerodynamic fairing over the sump and into the engine. The spinner must be lightweight yet able to withstand gas pressure loading and centrifugal loading without significant deflection even under maximum inlet distortion. The attachment system must be rigid enough to absorb the energy of a foreign object impact, and still be easily removed for maintenance purposes.

The edge attachment of the spinner would be a bolted design similar to the configuration depicted in Figure 15. In the 1979 design, the center portion of the spinner would incorporate an acoustical core, and the outer facing would be bonded to the structural filaments of the flange wrapped around the bolt holes. Although the composite replacement spinner would contain a composite flange, the weight of this spinner is heavier due to joint geometry.

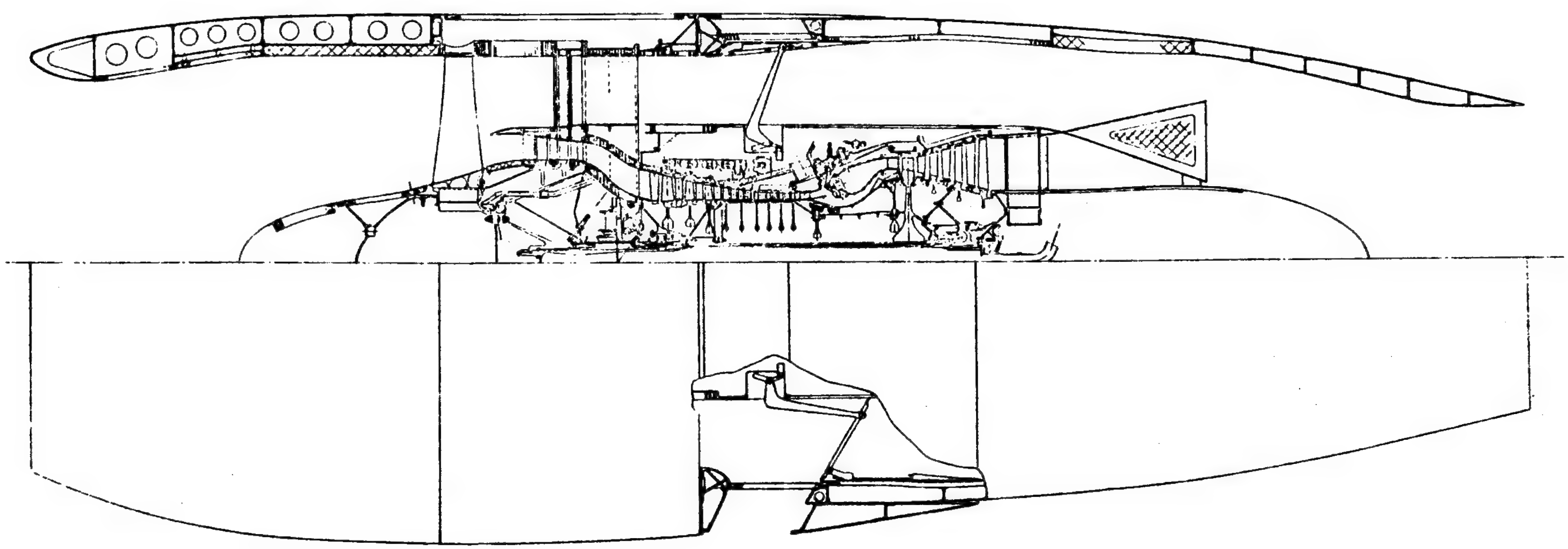


Figure 12. 1979 Composite Engine Cross Section.

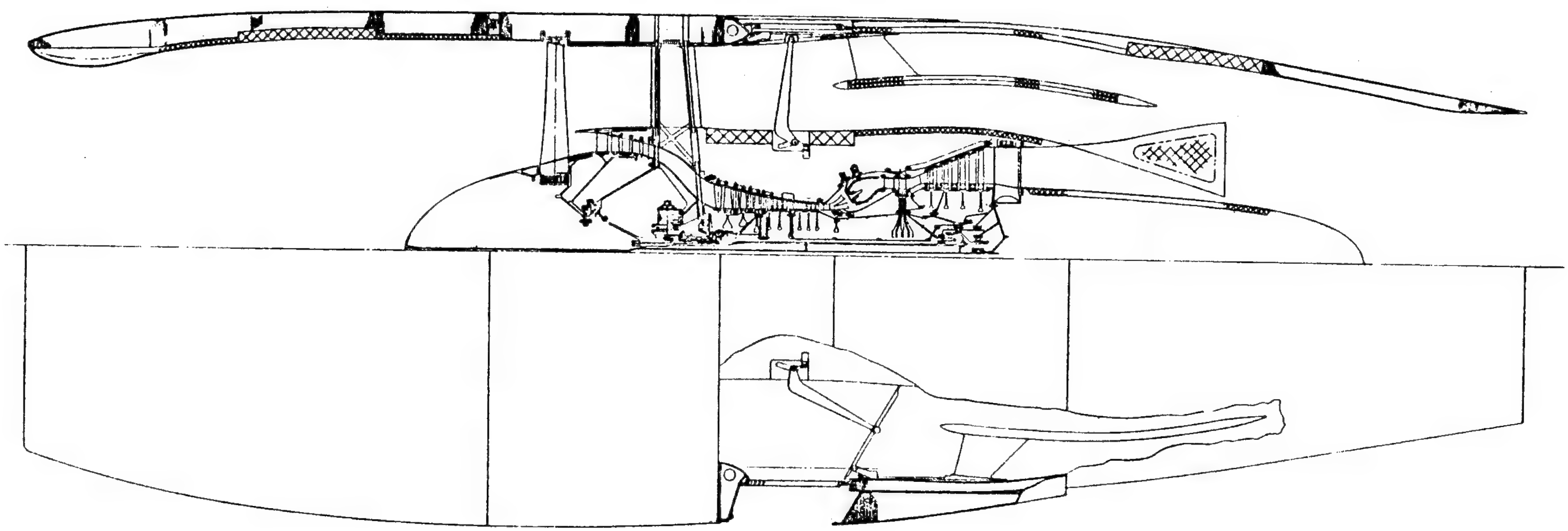


Figure 13. 1985 Composite Engine Cross Section.

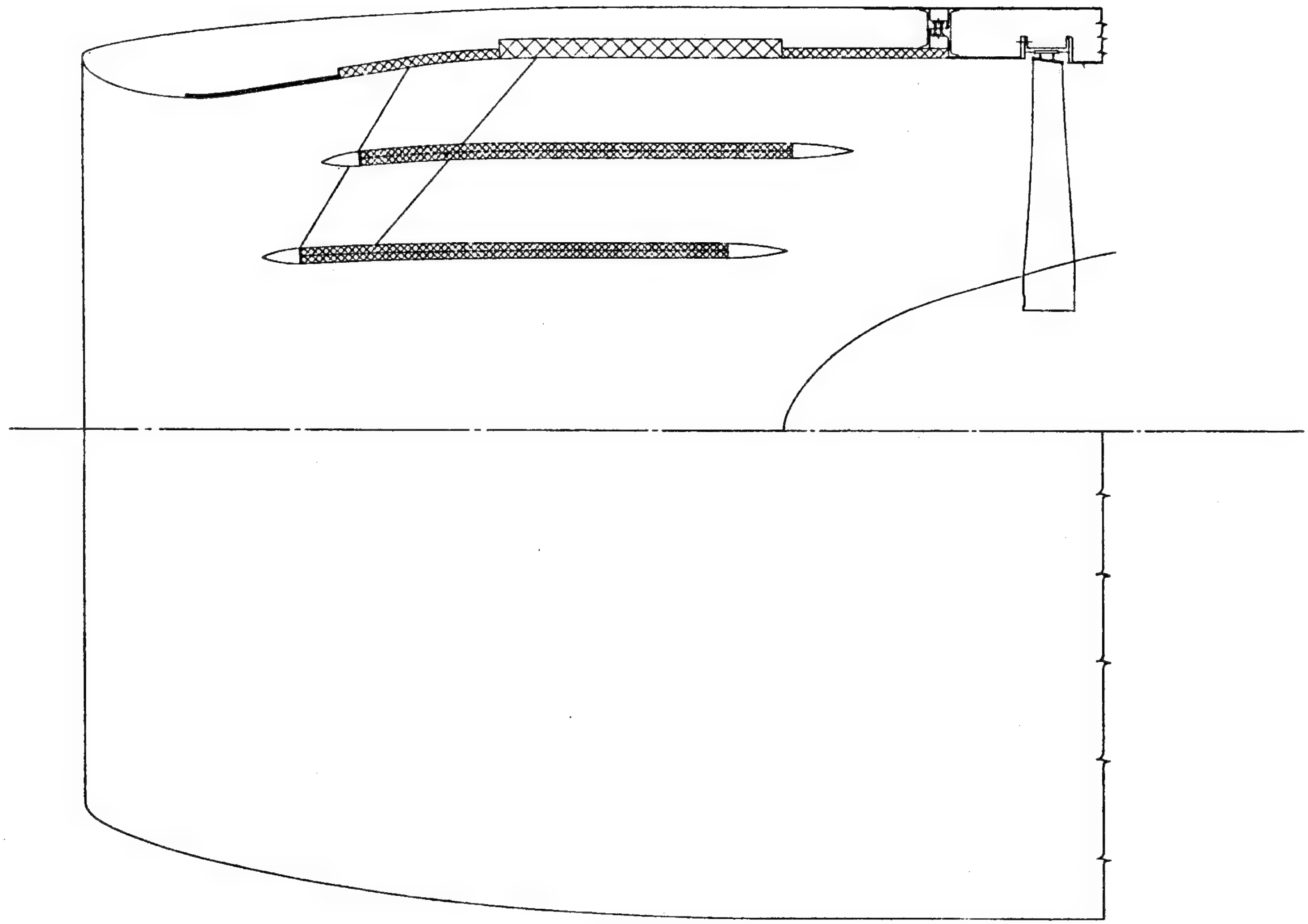


Figure 14. 1985 Alternate Inlet.

Table VI. Weight Breakdown of Acoustically Treated Composite Static Structures, kilograms (pounds).

Component	1979 Replacement	1979 Redesign	1985 Replacement	1985 Redesign
Spinner	29 (63)	23 (50)	N/A	N/A
Inner Duct				
• Acoustic Treatment	50 (111)	50 (111)	25 (55)	25 (55)
• Composite Structure	33 (73)	33 (73)	27 (60)	27 (60)
Outer Duct				
• Acoustic Treatment	113 (250)	113 (250)	57 (125)	57 (125)
• Composite Structure	161 (355)	161 (355)	136 (300)	136 (300)
Containment	136 (300)	113 (250)	125 (275)	68 (150)
Nacelle Shell	731 (1611)	731 (1611)	600 (1322)	588 (1297)
Acoustic Splitter				
• Acoustic Treatment	N/A	N/A	30 (67)	30 (67)
• Composite Structure	N/A	N/A	44 (96)	44 (96)

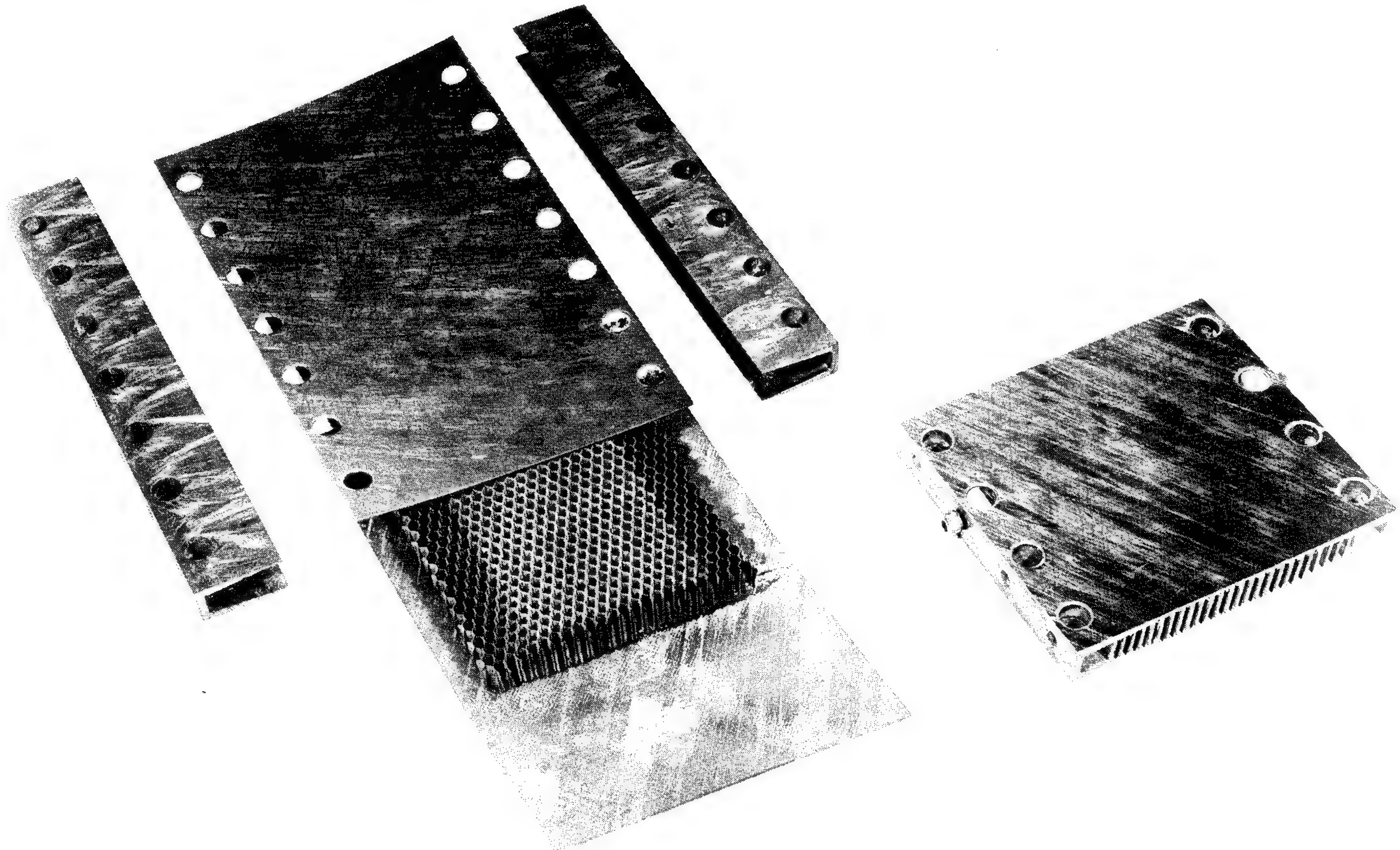


Figure 15. Typical Composite Duct Construction.

3.3.3 Fan Rotor Design

The fan design selected for evaluation and analysis in this program is an advanced 472 m/sec (1550 ft/sec) aerodynamic design. This design was selected as being the best compromise in terms of having baseline information already available for comparison and still keeping in close agreement with the 1979 and 1985 fan requirements. It was beyond the scope of this program to develop new fan blade geometry for the 1979 and 1985 engines.

The fan blade design study consisted of evaluating, primarily from a weight and cost standpoint, several fan blade mechanical designs, both metal and composite. The blade aero geometry in terms of camber, stagger, solidity and tm/c distributions are similar for all designs to keep to a minimum the differences in aerodynamic performance resulting from the different blade designs. The major difference existed in number of blades and corresponding increases or decreases in blade chord to provide the proper blade torsional stability parameter. The composite blade designs studied, for the most part, were of differing numbers of blades from the baseline 46 blade design and therefore could not be evaluated on a direct substitution basis, which would require flowpath modification to provide the proper axial spacing. This means that consideration would have to be given to increasing the casing length in composite blade designs of less number of blades than the baseline 46 blade design. Composite blades of the unshrouded type are in general not amenable to direct substitution due to the shear modulus of composite materials which result in unacceptable frequency characteristics. Direct substitution of composite blades in shrouded applications require the development of manufacturing technology in the area of individual blade shrouds and in significant improvements in FOD capability. This technology was not assumed to be available for the 1985 engine although the possible payoff in terms of weight are presented. The difference in the 1979 and the 1985 blades selected for this study results from using AU graphite in 1979 and advanced materials such as some improved form of GY70 graphite in 1985 assuming that the hybrid technique would be sufficiently developed to permit designing with the higher modulus material while still developing high strengths and retaining good FOD characteristics. To simulate this hybrid material, a composite with the strength of boron and a density of graphite was assumed.

The fan blade materials considered in whole or in combination for this study were:

- Titanium
- Graphite/epoxy
- Boron/epoxy
- PRD/epoxy
- Glass/epoxy

The epoxy resin system was assumed throughout as meeting the maximum blade temperature of 136° C (276°F).

Due to the low density of the composite blade materials, root centrifugal stress was not a limiting consideration. The

primary design setting criteria for the composite blades was reduced velocity ($V_R = V/_{bw}$, b = CHORD/2, V = relative velocity, w = torsional frequency) and first flex frequency. The reduced velocity and 1F/2/Rev criteria used was as follows:

	V_R	1F/2/REV
Tip Shrouded Blades	1.6 - Max.	1.15 Min.
Cantilevered Blades	1.4 - Max.	0.75 Max.

In some cases the designs evaluated are outside these limits but not by significant amounts. In these cases the blade would have to be tuned to provide the proper flex or torsional frequency.

The physical and mechanical properties for the composite materials used in the study are listed in Table VII. For blade designs having more than two composite materials with differing fiber layup, a computer program was used to arrive at the effective properties of the blade.

The bird impact considerations were limited to the selection of material combinations and fiber layup arrangements which were thought to provide adequate resistance to two-pound bird impact conditions.

The noise and performance considerations are as follows:

- Tip shrouded blades generally show a 0.5 point loss in fan efficiency as compared to unshrouded blades.
- Reduction in number of blades for a given fan aero design results in a loss in fan efficiency. Going from a 46 blade design down to a 22 blade design results in approximately 0.3 point loss in efficiency.
- Mid span shrouded blades can have considerable loss in fan efficiency depending on the shroud thickness and spanwise location.
- Reducing number of rotor blades (increasing blade chords) with increasing axial blade spacing can result in increased fan noise for unsuppressed fan engine. Number of rotor-stator chord spacing in a fully treated engine such as the 1979 and 1985 configurations however tends to be independent of overall noise levels.

Table VII. Composite Materials Properties.

Parameter	Graphite / Epoxy	Boron / Epoxy	S-Glass / Epoxy	PRD-49 / Epoxy	Hybrids: 80% Graphite / 20% S-Glass	Hybrids: 80% Graphite / 20% PRD-49	Fiber-B / Epoxy
Vp, %	60	55	60	60	60	60	60
E (0^o), 10^9 N/m^2	119	200	59	76	106	110	37
E (90^o), 10^9 N/m^2	11	12	8	6	10	10	6
E (0/22/0/-22) 10^9 N/m^2	95	117	47	59	86	89	32
G (0/22/0/-22) 10^9 N/m^2	11	19	6	6	10	10	6
ν (0/22/0/-22)	0.65	0.97	0.39	0.90	0.60	0.70	---
ρ, 10^3 kg/m^3	1.55	1.93	2.0	1.4	1.6	1.5	1.4
$\sqrt{Ex/\rho}$ (0/22) $10^3 \sqrt{m}$	7.8	7.8	4.8	6.5	7.3	7.7	4.8
$\sqrt{Gxy/\rho}$ (0/22) $10^3 \sqrt{m}$	2.7	3.1	1.7	2.1	2.5	2.6	2.1
Tensile Strength, 10^6 N/m^2 (0^o)	1378	1378	1378+	1378	1303	1213	1378
(0/22/0/-22) 10^6 N/m^2	951	951	951+	951	889	834	951
Flex Strength, 0^o, 10^6 N/m^2	1930	---	---	620	---	---	620
(0/22/0/-22) 10^6 N/m^2	1682	---	1724	586	---	---	586
Shear Strength, 0^o, 10^6 N/m^2	80	76	81	34-69	72	68	34-69
$\pm 10^o$ Charpy, joule	20	10	47	23	26	19	---
Blade Orientation (0,22)							
$\sigma^2/2E$ (Tensile) 10^3 N/m^2	4757	3861	9652+	7653	---	---	14272
$\sigma^2/2E$ (Flexural) 10^3 N/m^2	13237	---	31716	2896	---	---	5412
Equivalent	---	---	---	22752*	---	---	16547**

* Estimated for PRD Hybrid/Glass   ** B Fiber/S-Glass Hybrid

Table VII. Composite Materials Properties (Concluded).

Parameter	Graphite/Epoxy	Boron/Epoxy	S-Glass/Epoxy	PRD-49/Epoxy	Hybrids: 80% Graphite/20% S-Glass	Hybrids: 80% Graphite/20% PRD-49	Fiber-B/Epoxy
Vp, %	60	55	60	60	60	60	60
E (0°), 10^6 psi	17.2	29.0	8.5	11.0	15.4	15.9	5.4
E (90°), 10^6 psi	1.6	1.8	1.1	0.8	1.5	1.4	0.8
E (0/22/0/-22), 10^6 psi	13.8	17.0	6.8	8.6	12.5	12.9	4.6
G (0/22/0/-22), 10^6 psi	1.6	2.7	0.9	0.93	1.46	1.47	0.85
υ (0/22/0/-22)	0.65	0.97	0.39	0.90	0.60	0.70	---
ρ, lb/in^3	0.056	0.070	0.072	0.050	0.059	0.055	0.050
$\sqrt{Ex/\rho}$ (0/22) $\sqrt{in}$	15.7	15.6	9.7	13.3	14.6	15.3	9.6
$\sqrt{Gxy/\rho}$ (0/22) $\sqrt{in}$	5.35	6.2	3.5	4.3	4.97	5.16	4.1
Tensile Strength, 0°, ksi	200	200	200+	200	189	176	200
(0/22/0/-22), ksi	138	138	138+	138	129	121	138
Flex Strength, 0°, ksi	280	---	---	90	---	---	90
(0/22/0/-22), ksi	244	---	250	85	---	---	85
Shear Strength, 0°, ksi	11.6	11.0	11.8	5 - 10	10.5	9.8	5 - 10
±10° Charpy, ft lb	15	7.5	35	17	19.4	14.0	---
Blade Orientation							
$\sigma^2/2E$ (Tensile) psi	690	560	1400+	1110	---	---	2070
$\sigma^2/2E$ (Flexural) psi	1920	---	4600	420	---	---	785
Equivalent	---	---	---	3300*	---	---	2400**

* Estimated for $\frac{\text{PRD/Hybrid}}{\text{Glass}}$ ** B Fiber/S-Glass Hybrid

Since the baseline metal blades are tip shrouded, and the composite blades selected for both the 1979 and 1985 engines are cantilevered, a 0.5 point gain in efficinecy results. However since the composite rotors selected have far fewer blades, resulting in a typical 0.3 point loss in efficiency, there is about an even trade in fan efficiency.

A summary of the 14 blade configurations evaluated in this program is provided in Table VIII. The first configuration represents the baseline titanium blade design having 46 blades with tip shrouds. All other designs are compared to this design for overall rotor weight savings.

The composite tip shrouded configurations were considered to be a technology needing more manufacturing and bird impact development before being ready for advanced applications, but the potential payoffs for these blades are shown for reference.

The various unshrouded designs were assumed to apply to both the 1979 and 1985 engines.

Several spar/shell designs were considered for comparison with the solid composite design.

The solid graphite/epoxy blades were presented primarily for comparison with the hybrid flex root blade designs and were not intended as designs which could pass the .9 kilogram (2 lb) bird impact requirements.

The cantilevered flex root blade design with the AU graphite material is shown in Figure 16, indicating the fiber arrangement and orientation angles.

The basic points to consider in evaluating the data in Table IV are as follows:

- FOD capability of designs are not necessarily equal.
- Heavier blades generally provide higher impact resistance.
- Tip shrouding has potential for load sharing during impact.
- Pinned root configurations permit more deflection and centrifugal recovery thereby increasing impact capability.

Table VIII. NASA Cost and Benefits Study Fan Rotor Weight Summary.

Item	Solid Titanium Tip Shrouded	Solid Gr/Ep Tip Shrouded*‡	Ti Spar Blade Tip Shrouded*§	S-Glass Tip Shroud*	Hybrid W/Boron Tip Shroud*	Hybrid W/Boron Tip	Titanium Spar Cantilevered§	Titanium Hollow Spar Cantilevered§	Holey Spar Cantilevered§	Spar Blade Pinned Root§	Solid Graphite Epoxy Cantilevered	Hybrid Flex Root w/AU Cantilever	Hybrid Flex Root w/Boron Cantilever	Advanced Graphite/ Hybrid Flex Root Cantilevered
Number of Blades	46	46	52	32	46	46	26	26	26	26	22	22	22	28
Blade Wt: Total, kg Total, lbs	105 232	51 113	58 129	74 164	38 85.0	38 85.0	94 208	87 192	87 192	97 214	71 156	66 145	68 152	65 143
Single, kg Single, lbs	2.3 5.04	1.1 2.46	1.1 2.48	2.3 5.11	0.8 1.85	0.8 1.85	3.6 8.01	3.3 7.39	3.3 7.39	3.7 8.22	3.2 7.08	3.0 6.6	3.1 6.9	2.3 5.1
Disc Wt, kg Disc Wt, lbs	75 165	36 79	33 73	71 156	48 106	48 106	72 158	68 151	68 151	74 164	69 152	67 148	68 150	--- ---
Reduced Velocity Parameter†	1.6	1.55	1.6	1.56	1.66	1.40	1.37	1.37	1.37	1.37	1.45	1.76	1.39	1.32
Total Rotor Weight, kg lbs	180 397	87 192	92 202	145 320	87 191	87 191	166 366	155 343	155 343	176 388	140 308	133 293	137 302 1979 Engine	127 280 1985 Engine

* Composite Tip-Shrouded Designs for Reference Only.

† Reduced Velocity Parameter = (Average Relative Air Velocity Over Outer 1/3 of Span, ft/sec) ÷ [(1/2 Chord at 5/6 Span, ft) X (1st Torsional Frequency at Design rpm, radians/sec)]

‡ Graphite/Epoxy Shell with [0,±22] Lay-up

§ Graphite/Epoxy Shell with [0,±45] Lay-up

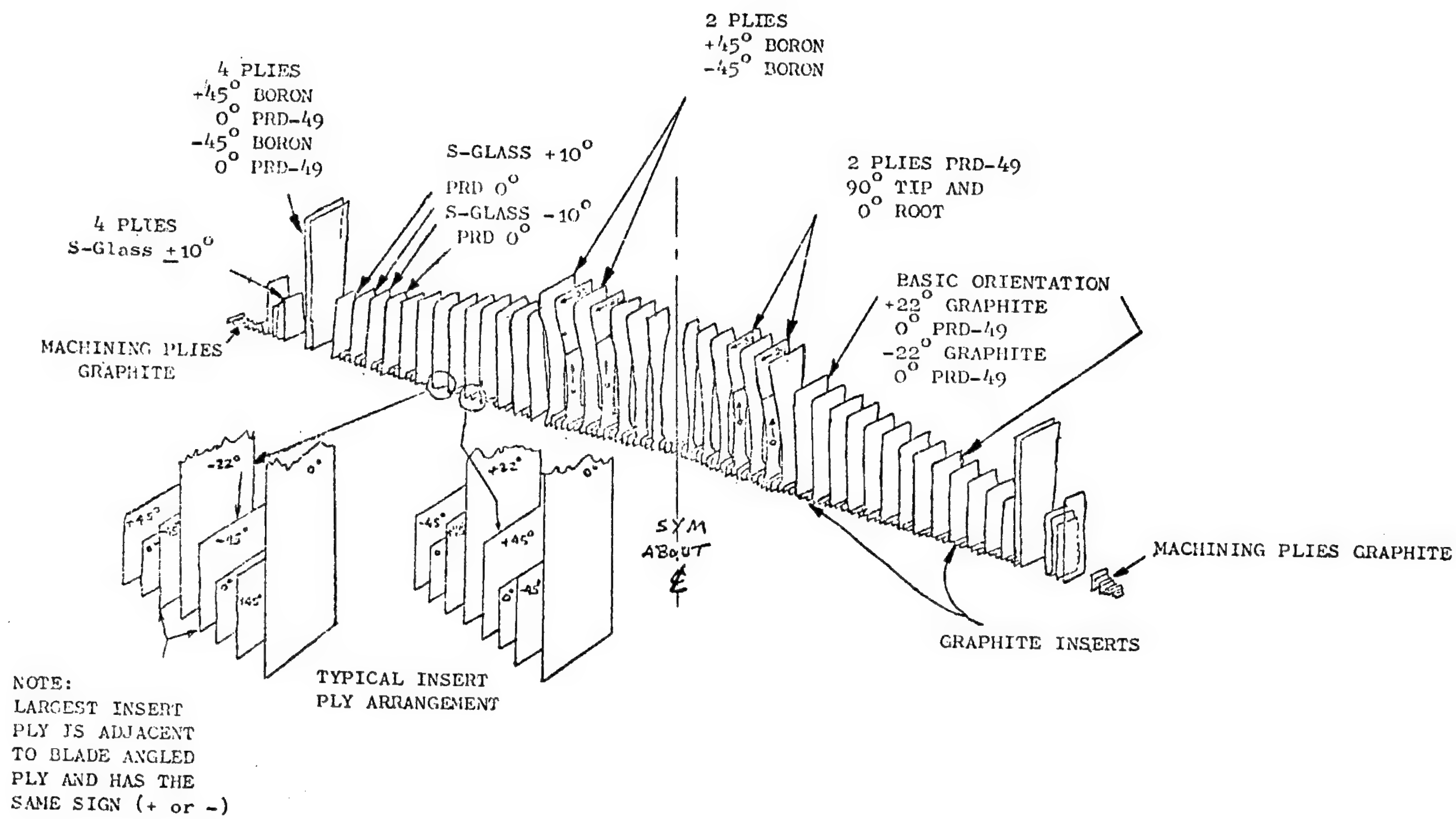


Figure 16. Typical Composite Blade Arrangement.

- Titanium has greater impact capability because of its higher toughness and ability to plastically deform but often leads to greater secondary damage.
- Metal blades require more containment for the same blade weight.
- Hybrid flex root blades offer greater impact resistance for composites.
- The spar/shell blades considered may offer greater gross impact capability compared to an all composite design but are likely to yield lower initial threshold damage due to interface characteristics.
- Spar/shell designs will most likely be more expensive to manufacture than composite blades.

An overall evaluation of this data indicates that both the 1979 and 1985 engines would contain composite flex root cantilevered blades.

For the 1985 engine, tip shrouded hybrid composite blades offer greater weight saving potential providing manufacturing and impact technology is available.

As mentioned above, composite blades require less containment for the same blade weight than metal blades due to the way the composite material fails. The weight of the required containment is included in the nacelle weight but is mentioned here because the reduction in containment weight is directly related to having composite blades. Since the 1979 replacement concept does not have composite blades, a metal containment weight of 136 kilograms (300 lb) was chosen as typical. In the 1979 redesign which does have composite blades, it was assumed that 113 kilograms (250 lb) of metal containment would be required. For the 1985 replacement concept, which again had metal blades, a metal containment of 125 kilograms (275 lb) was used which assumed some improvement in containment technology. For the 1985 redesign engine with composite blades, a fiber/felt arrangement was used which produced a containment weight of 68 kilograms (150 lb).

3.3.4 Booster Blade Design

Stages 2 and 3 booster blades were considered for composites on a direct substitution basis. The dovetail configuration for composite blades will be consistent with current large composite fan blade designs having a bell-shaped pressure face and possibly having a swing root outsert. The thinness of the small booster forces the blades to be solid instead of hollow.

3.3.5 B/Al First Stage Compressor Design

The application of boron/aluminum composite material in the first stage compressor blade was studied. The results of this study indicated that use of B/Al was technically feasible; however, the only apparent advantage was a relatively small weight reduction. Further development of this component was not recommended as the study indicated the B/Al blade would cost considerably more than the titanium blade even in the 1985 time period.

The first stage compressor stage contains 38 cantilevered titanium blades. The tip speed is 1550 ft/sec with a maximum operating temperature of 530^{o}F. The blade airfoil is 3.36 inches long with a root chord of 2.19 inches. The titanium blade weights .183 pounds.

The equivalent B/Al blade is technically feasible in consideration of application temperatures and stresses. There is no aerodynamic advantage in using B/Al; however, the chord can be reduced approximately 12%. This would reduce the compressor and overall engine length by .162 inch. The number of blades would increase to 42 to maintain the aerodynamically required solidity. The B/Al blade weight would be .104 pounds. Considering the difference in the number of blades, reduction in the disc weight, and further reductions by reducing the compressor length, the total weight reduction would be approximately 4.51 pounds.

A comprehensive cost analysis was conducted. The cost of both the titanium and B/Al blades was projected to the 1985 time period. Based on a 600 titanium blade lot and 660 B/Al blades, accounting for the greater number of B/Al blades required per stage; the B/Al blades would cost 11% more than the titanium blades. Based on 2000 titanium and 2200 B/Al blade lots, the B/Al blades would cost 64% more than the titanium blades. These estimates do not include development or tooling costs which would be considerably higher for the B/Al than the titanium blades.

3.3.6 High Pressure Turbine Design

Possible benefit of using advanced composite materials in the HPT area were explored by considering its use on a 1985 engine design. A base turbine design was carried out using a currently available high temperature nickel superalloy designated Rene' 120. A R120 bladed turbine was designed and its weight and required cooling determined. Two composite blade materials were then substituted into the design. The first material was a eutectic alloy called advanced NiTac while the second was the tungsten wire/superalloy composite. The benefits and penalties of using the two advanced materials were determined by comparing the resulting design with the base design. Figure 17 summarizes the blade material definition.

Allowable blade bulk metal temperatures were determined by applying commercial life requirements for the blade while satisfying a typical CF6-6 engine commercial mission. For the HPT blade of R120, an allowable bulk metal temperature of 921°C (1690°F) was set. Figure 18 describes the process of setting the allowable bulk metal temperature. Advanced NiTac and the tungsten wire/superalloy composite blade allowable temperature was set at a range of 1004°C (1840°F) to 1088°C (1990°F) to explore the possible range of material capability. The key assumption is that all critical blade properties will be equivalent to the base design at the elevated temperatures.

The turbine blade and disc system was modeled after an existing design but scaled to the proper thrust size. The design used an unshrouded, long chord airfoil retained by a multiple tang dovetail. HPT blade weight was scaled to permit an accurate determination of the blade dead loads. The base case and all composite blade designs used a Rene' 95 material disc. Figure 19 summarizes the procedure followed. Additional designs were made with the advanced NiTac and tungsten wire superalloy blades for the same cycle conditions. Figure 20 presents the cycle gas temperatures and the conversion to design relative gas temperatures. Tables IX and X show the weight difference between each design.

Three different cooling technologies (and effectiveness) were assumed for the HPT blades in this study. Blade cooling system schematics are shown in Figure 21 for each of the technologies. The first, called advanced film cooling, employs an insert with impingement cooling on the inner surface and film cooling on the outer blade surface involving large numbers of small holes. It is representative of the cooling technology that should be available for a 1985 engine where high cooling is required.

The second cooling technology, designated advanced convection cooling, assumed an impingement insert but only trailing edge discharge. It would be employed where only moderate cooling is required or where holes in the blade are unacceptable.

A third cooling technology, designated current film cooling, is representative of advanced cooling now being employed on HPT blades in General Electric engines. An insert supplies internal impingement cooling while a limited number of so called "gill holes" provides film cooling over the most critical blade heat transfer area. Cooling effectiveness of this approach lies between the advanced film cooling method and the advanced convection cooling method.

A heat transfer analysis was performed to determine the amount of cooling air needed to keep the advanced material at the specified bulk metal temperature. For the HPT blade, Figure 22 shows the cooling air required as a factor of metal temperature and cooling technology. The cooling effectiveness applicable to each of the cooling technologies was used in this analysis. Engine thrust and cycle temperatures and pressure were maintained. Changes in cooling air requirements were then reflected by changes in core size and SFC. Tables IX and X present the SFC differences resulting from the HPT blade material substitution referenced to the base R120 HPT blade design.

Cost differences shown in Tables IX and X reflect only the costs due to resizing the core engine. Blade material cost differences are not included but the effects of a range of cost are covered in Section 3.6. Weight changes shown are due to core size change and to design changes due to the substitution of the advanced turbine blade composite material.

3.3.7 Low Pressure Turbine Design

A highly loaded four stage LPT for an advanced 1985 engine was used to evaluate the effects on design weight and cooling of the advanced composite blading materials. As in the HPT blade design, allowable bulk metal temperatures were set by evaluating expected life and stress conditions. In the case of the LPT, however, only convection plus limited impingement type cooling was used for all cooled blades. More advanced film cooling is not needed for the amount of cooling required. Also, there is difficulty in using elaborate inserts in the longer, highly twisted LPT blading. Figure 23 shows the cooling flow required for the LPT.

As was done for the HPT, weight and SFC effects were calculated for each of the materials. Table XI presents the results along with the assumed allowable metal temperatures. Again, cost effects are for the changes in core size only due to changes in required cooling flow. Cost effects due to blade material changes were not considered here but are dealt with in Section 3.6.

I Base Design Material — Rene' 120

Currently Used on F101 and ATEGG Demonstrators

Approximately 28°C (50°F) Higher Allowable Temperature than CF6 Blading Material

II Advanced Eutectic Alloy — (A) NiTac

Studied with 83 - 167°C (150 - 300°F) Higher Allowable Temperature than R120 Base

III Advanced Composite Alloy — Tungsten Wire - Super Alloy Composite

Studied with 83 - 167°C (150 - 300°F) Higher Density Corrected Allowable Temperature than R120 Base

Density Assumed 18% Greater than above Materials

Figure 17. Blade Material Definition.

I Pitch Line Blade Stress Levels Were Determined for Each Design.

II Limiting Stress Condition Was Determined for R120 by

A. Setting Equivalent Life at T/O Temperatures

B. Applying Equivalent Life Requirement on Allowable Temperatures for

1.	Stress Rupture	938°C (1720°F)	
2.	1 % Creep	921°C (1690°F)	Limiting
3.	Low Cycle Fatigue	927°C (1700°F)	

C. Setting Allowable Temperature by Limiting Stress Conditions

III Creep and Low Cycle Fatigue Were Limiting in R120 Design at 921°C (1690°F)

IV Temperature Adders Were Applied for Each Material on R120 Base

R120 + 83°C (150°F) = 1005°C (1840°F)

R120 + 167°C (300°F) = 1088°C (1990°F)

V All Critical Blade Properties Were Assumed Equivalent at the Elevated Temperatures. Adequate Blade Coatings also Assumed to be Available.

Figure 18. Allowable Blade Temperature Method.

Base Engine -	1985 Advanced Technology Engine with Best Current Blade Materials.
Life Requirement -	Consistent with Typical CF6 Commercial Mission and Use. All Blades Designed to Same Life.
Blade Temperature Limits -	Bulk Blade Metal Temperatures Set to Meet above Life Requirements with Imposed Operating Stresses.
Blade Relative Gas Temperatures -	Average Pitchline Cycle Temperatures Adjusted for Margin (Tolerances, Transients, Deterioration) with Vector Velocity Effects Incorporated. Pitchline Temperatures Include Radial Profile Effects.
Cooling Flows -	Determined by Calculating Cooling Flow Needed for Assumed Cooling Technology Effectiveness to Attain Bulk Temperature Limits.
Material Density Effects -	Constant Stress Designs used in Supporting Structures along with Part Weights Calculated.
Core Scaling Effect -	Core Size Scaled with Required Cooling Flow to Keep Constant Thrust Engine with Given Fan Size. Weight and Cost Scaled Accordingly.

Figure 19. Design Evaluation Procedure.

	HPT	LPT Stg. 1	LPT Stg. 2
Ave. Cycle Temperature (Blade Inlet)	(2800°F) 1538°C	(2080°F) 1138°C	(1880°F) 1027°C
Margin plus Profile Effect.	(+280°F) +156°C	(+220°F) +122°C	(+200°F) +111°C
Design Abs. Temp. @ Pitchline	(3080°F) 1693°C	(2300°F) 1260°C	(2080°F) 1138°C
Adjustment for Vector Diagram & Recovery Effects	(-420°F) -233°C	(-120°F) -67°C	(-110°F) -61°C
Design Relative Temperature @ Pitchline	(2660°F) 1460°C	(2180°F) 1193°C	(1970°F) 1077°C

Figure 20. Gas Temperature Levels.

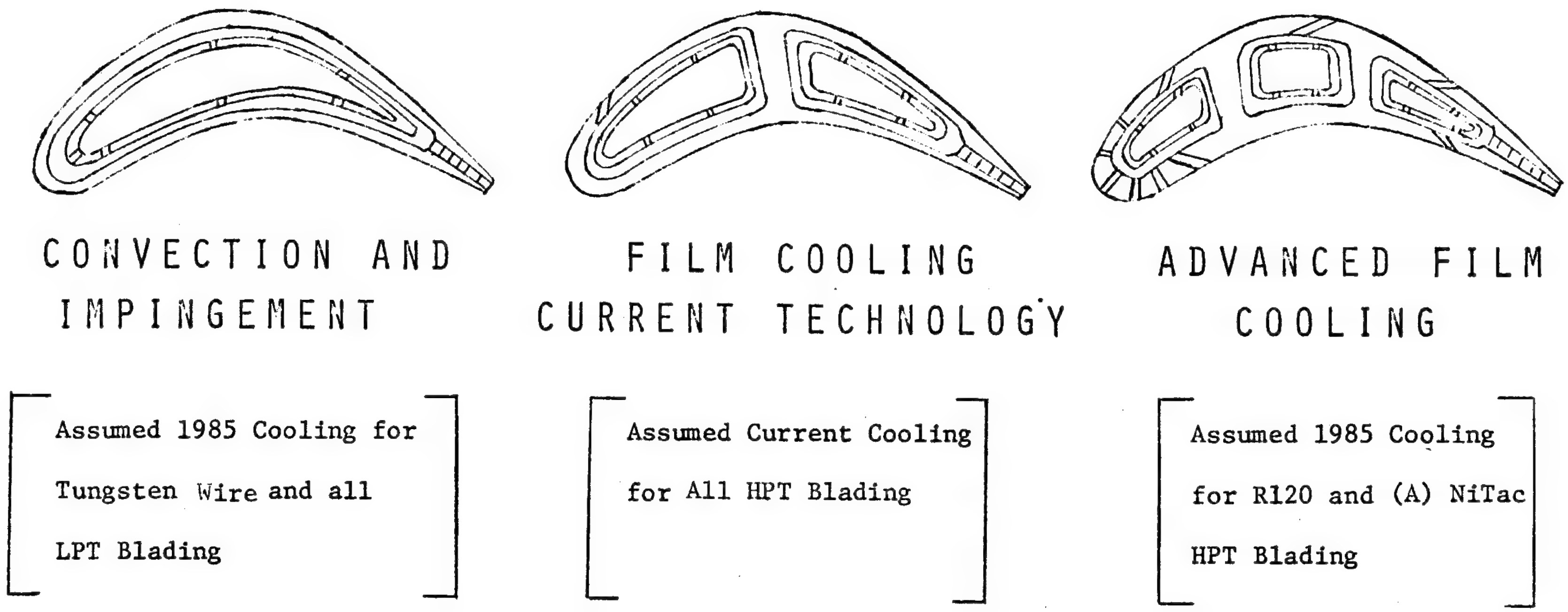


Figure 21. Turbine Cooling Technology Levels.

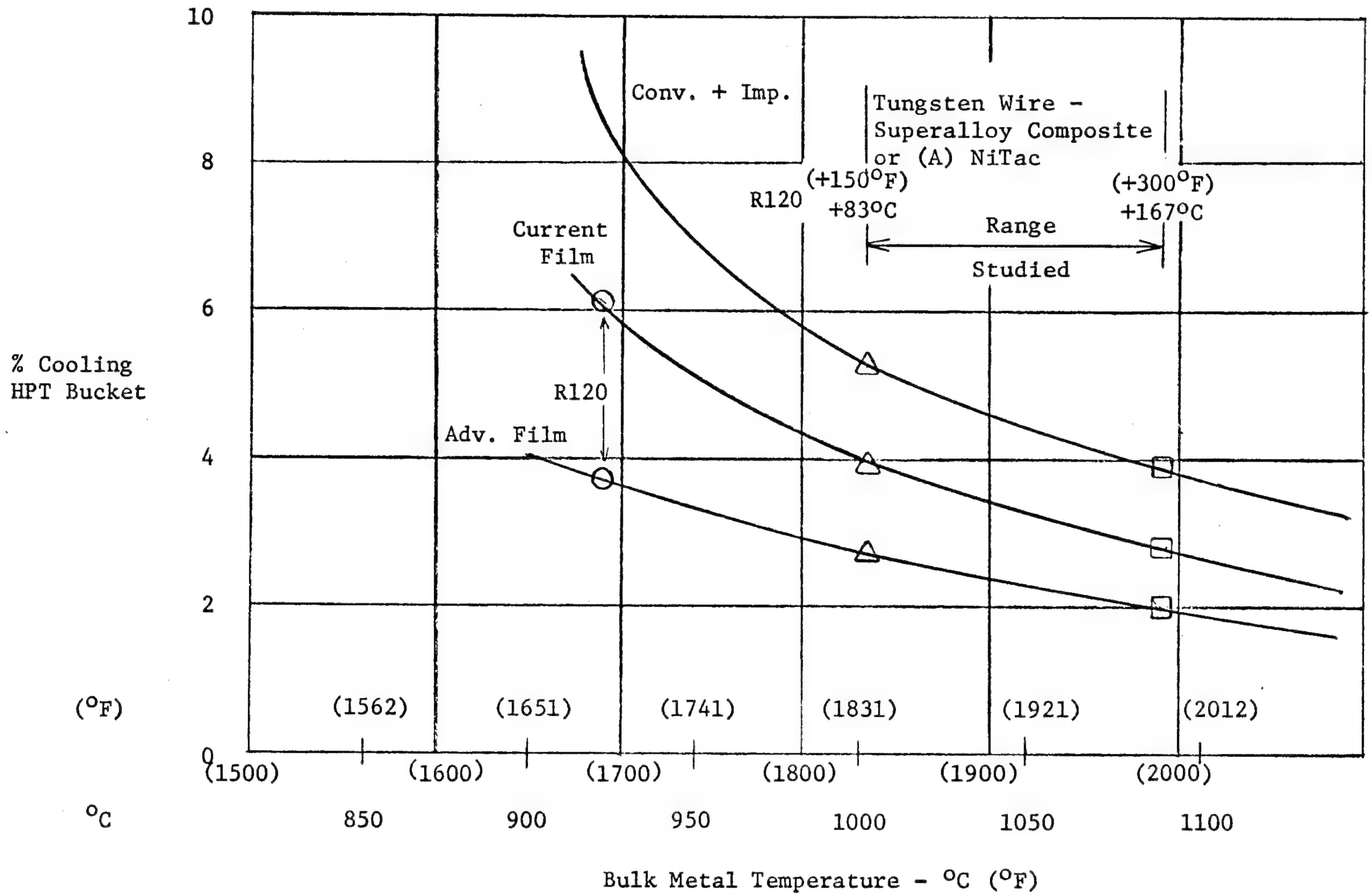


Figure 22. HPT Blade Cooling Requirements.

Table IX. Effect of Utilization on Advanced Ni Tac HPT Blade Material (Single Stage Only).

	Base		Advanced Ni Tac					
Fn, N (lbs)	119212 (26800)							
Fan Dia. m (in.)	1.74 (68.5)							
Fan Corr. Flow @ 100% kg/sec (lb/sec)	430 (947)							
Δ% Core Flow Size	Base		-1.4					
T/O T_4, °C (°F)	1538 (2800)							
HPT Blade Material	R120		Advanced Ni Tac					
T Bulk Design, °C (°F)	921 (1690)		1005 (1840)			1088 (1990)		
Cooling Technology	Adv. Film	Cur. Film	Adv. Film	Cur. Film	Conv.+ Imp.	Adv. Film	Cur. Film	Conv.+ Imp.
HPT Blade Cooling, W/W_{2C}, %	3.7 (Base)	6.1	2.7	3.9	5.9	2.0	2.7	3.9
Total HPT W/W_{2C}, %	5.0	7.4	4.0	5.2	7.2	3.3	4.0	5.2
Total W/W_{2C},%	0	2.4	-1.0	+ .2	+2.2	-1.7	-1.0	+ .2
Δ Engine Weight (Scaling), kg (lb)	Base	+42 (+93)	-18 (-40)	+4 (+9)	+38 (+84)	-30 (-66)	-18 (-40)	+4 (+9)
Δ Engine Weight HPT Material Change, kg (lb)		0	0	0	0	0	0	0
Δ Engine Weight Total, kg (lb)		+42 (+93)	-18 (-40)	+4 (+9)	+38 (+84)	-30 (-66)	-18 (-40)	+4 (+9)
Δ% SFC		.6	-.2	0	+.1	-.5	-.3	0
Δ Engine Cost (Scaling), 1000 $		+18	-8	+2	+16	-13	-8	+2

Table X. Effect of Utilization of Tungsten Wire-Superalloy Composite HPT Blade Material.

SINGLE STAGE TURBINE

	Base		Tungsten Wire-Superalloy Composite					
Fn, N (lbs)	119212 (26800)	→	→	→	→	→	→	→
Fan Dia., m (in.)	1.74 (68.5)	→	→	→	→	→	→	→
Fan Corr. Flow @ 100% kg/sec (lb/sec)	430 (947)	→	→	→	→	→	→	→
Δ% Core Flow Size	Base		+ .4					
T/O T_4, ^oC (^oF)	1538 (2800)	→	→	→	→	→	→	→
HPT Blade Material	R120		Tungsten Wire-Superalloy Composite					
T Bulk Design, ^oC (^oF)	921 (1690)		1005 (1840)			1088 (1990)		
Cooling Technology	Adv. Film	Cur. Film	Adv. Film	Cur. Film	Conv.+ Imp.	Adv. Film	Cur. Film	Conv.+ Imp.
HPT Blade Cooling, W/W_{2C}, %	3.7 (Base)	6.1	2.7	3.9	5.9	2.0	2.7	3.9
Total HPT W/W_{2C}, %	5.0	7.4	4.0	5.2	7.2	3.3	4.0	5.2
Total $\Delta W/W_{2C}$, %	0	+2.4	-1.0	+.2	+2.2	-1.7	-1.0	+.2
Δ Engine Weight (Scaling), kg (lb)	Base	+42 (+93)	-18 (-40)	+4 (+9)	+38 (+84)	-30 (-66)	-18 (-40)	+4 (+9)
Δ Engine Weight HPT Material Change, kg (lb)	↓	0	+9 (+19)	+9 (+19)	+9 (+19)	+9 (+19)	+9 (+19)	+9 (+19)
Δ Engine Weight Total, kg (lb)	↓	+42 (+93)	-9 (-21)	+13 (+28)	+47 (+103)	-21 (-47)	-9 (-21)	+13 (+28)
Δ% SFC	↓	.6	-.2	0	+.6	-.4	-.3	0
Δ Engine Cost (Scaling), 1000 $	↓	+18	-8	+2	+16	-13	-8	+2

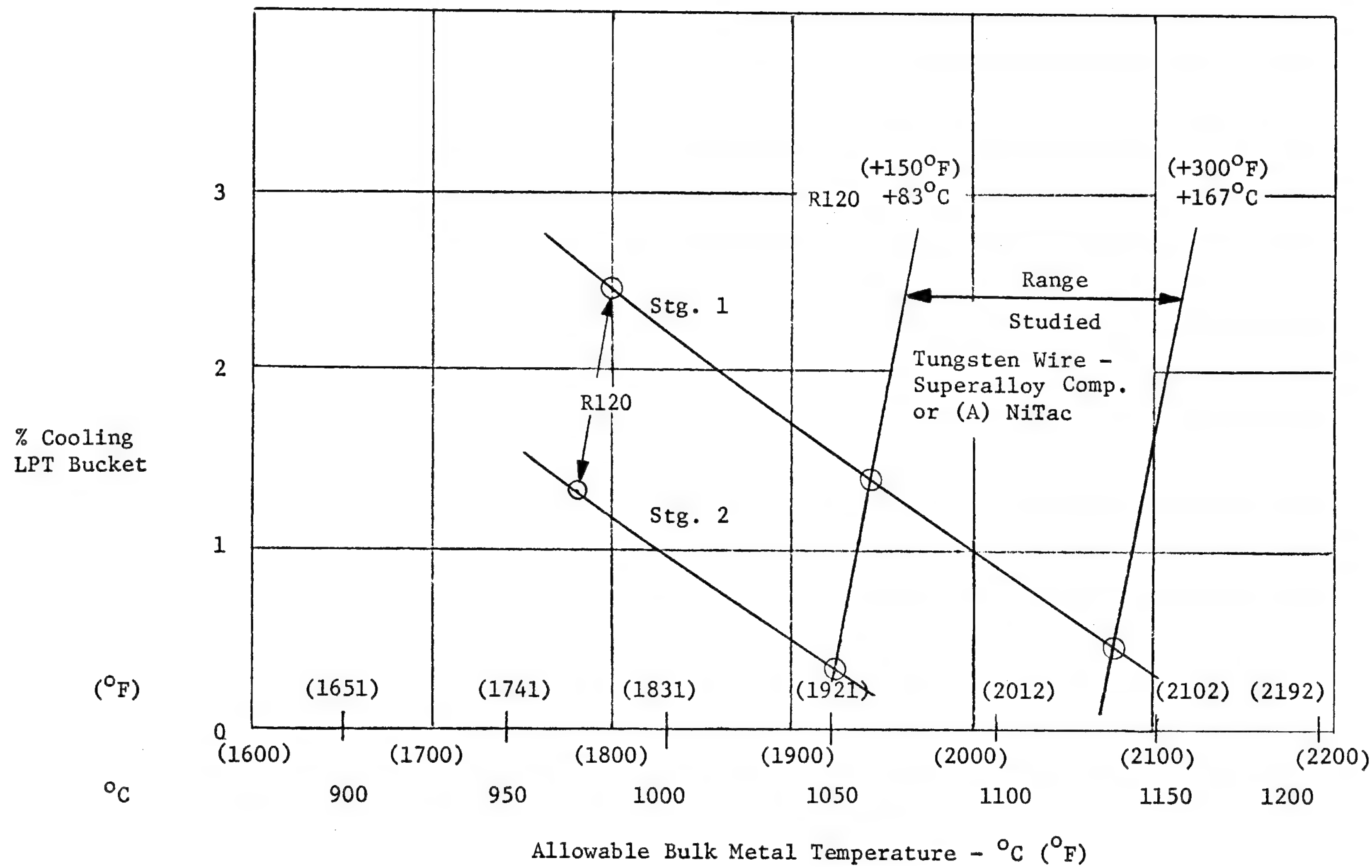


Figure 23. LPT Blade Cooling Requirements.

Table XI. Effect of Eutectic and Tungsten Wire Utilization in LPT Blades (4-Stage LPT Only).

CONVECTION AND IMPINGEMENT COOLING ONLY

	Base		(A) Ni Tac				Tungsten Wire			
Fn, N (lbs)	119212 (26800)									
Fan Dia., m (in.)	1.74 (68.5)									
Fan Corr. Flow @ 100%, kg/sec (lb/sec)	430 (947)									
△% Core Flow Size	Base		-3.2				-5.6			
T/O T_4, °C (°F)	1538 (2800)		1538 (2800)				1538 (2800)			
HPT Blade Material	R120		R120				R120			
Stage	1	2	1	2	1	2	1	2	1	2
LPT Blade Material	R120		(A) Ni Tac				Tungsten Wire			
Temperature Range			Lower		Upper		Lower		Upper	
T Bulk Design, °C (°F)	982 (1800)	971 (1780)	1065 (1950)	1055 (1930)	1149 (2100)	1138 (2080)	1066 (1950)	1055 (1930)	1149 (2100)	1138 (2080)
Blade Cooling Flow, %	2.45	1.27	1.37	.33	.46	0	1.37	.33	.46	0
Rotor Leakage Flow, %	.25	.25	.25	.25	.25	.25	.25	.25	.25	.25
Total Cooling Flow, %	2.70	1.52	1.62	.58	.71	.25	1.62	.58	.71	.25
Cooling Technology	Adv. Conv.		Conv. + Imp.				Conv. + Imp.			
Total △% Cooling, W/W_{2C}	Base		-2.0		-3.3		-2.0		-3.3	
△Weight Core Scaling, kg (lb)	Base		-36 (-80)		-58 (-128)		-36 (-80)		-58 (-128)	
△Weight LPT Mat., kg (lb)			0		0		+1 (+3)		+1 (+3)	
△Weight Total, kg (lb)			-36 (-80)		-58 (-128)		-35 (-77)		-57 (-125)	
△% SFC			-.34		-.53		-.34		-.53	
△Engine Cost (Scaling), 1000 $			-16		-25		-16		-25	

The most significant effect of switching from R120 in the first two cooled LPT stages to Advanced NiTac and the tungsten wire-superalloy composite material was the decrease in the required cooling flow. When the upper range of allowable metal temperature is used, one cooled stage is eliminated.

3.3.8 Weight Summary

This section presents a summary of the weight savings available to the components previously discussed through the use of composite materials.

In order to provide a consistent basis of comparison with existing components, the weights of the various composite components described above were combined in a slightly different grouping than shown in the component drawings. This was necessary to account for the more unitized composite configurations as compared to the more modular metal construction. This reassignment of weights and component definitions is shown in Table XII.

To make maximum use of available data some of these components were of slightly different sizes for different thrust size engines. To make the data more meaningful, it was scaled to a constant thrust size engine and these data are presented in Table XIII.

Table XII. Weight Comparison, kilograms (pounds).

Component	1979		
	Baseline	Replacement	Redesign
Nacelle[1]	1560 (3440)	1225 (2700)	1202 (2650)
Spinner	32 (70)	29 (63)	23 (50)
Stator Case Ass'y[3]	315 (695)	180 (396)	166 (367)
Fan Frame	297 (655)	177 (390)	160 (353)
Fan Rotor Ass'y[5]	180 (397)	N/A	137 (302)
Booster Blades	9 (20)	6 (13)	6 (13)
		1985	
Nacelle[2]	1293 (2850)	1043 (2300)	975 (2150)
Stator Case Ass'y[4]	107 (235)	57 (125)	57 (125)
Vane Frame	336 (740)	254 (560)	233 (513)
Fan Rotor Ass'y[5]	180 (397)	N/A	127 (280)
Booster Blades	9 (20)	6 (13)	6 (13)

[1] Structure Consists of Inner and Outer Duct, Containment, and Nacelle Shell

[2] Structure Consists of Inner and Outer Duct, Containment, Acoustic Splitter, and Nacelle Shell

[3] Structure Consists of Bypass Stator Case and Booster Stator Case

[4] Structure Consists of Only Booster Stator Case

[5] Structure Consists of Blades and Disc

Table XIII. Scaled Weight Comparison, kilograms (pounds).

Component	1979					
	Baseline		Replacement		Redesign	
Nacelle	1195	(2,634)	938	(2,067)	920	(2,029)
Spinner	23	(50)	20	(45)	16	(35)
Stator Case Ass'y	229	(504)	130	(287)	121	(266)
Fan Frame	213	(469)	127	(279)	114	(252)
Fan Rotor Ass'y	184	(406)	N/A		140	(309)
Booster Blades	14	(30)			9	(20)
	1985					
Nacelle	990	(2,182)	799	(1,761)	747	(1,646)
Stator Case Ass'y	77	(170)	41	(90)	41	(90)
Vane Frame	240	(530)	182	(401)	166	(367)
Fan Rotor Ass'y	184	(406)	N/A		130	(286)
Booster Blades	8	(17)	5	(11)	5	(11)

3.4 COMPOSITE COMPONENT FABRICATION

In order to obtain a reasonable estimate of the costs of the various components involved, it was necessary to consider in some detail the methods by which these components could be fabricated. Descriptions of the fabrication concepts utilized for the cost determinations are shown below for several of the components which appeared to have the most significant payoff.

3.4.1 Fan Blades

The composite blade configuration is a highly sophisticated design consisting of a complex airfoil shape (see Figure 24). In this respect it is much like a standard type propeller except that it has a much greater twist in the airfoil from its tip to the dovetail-like shape at its root. Complex airfoils of this type are developed by stacking well-defined lofted patterns layer on layer. Each layer represents a lofted elevation of an external profile much like a contour map defines the relationships of changing elevations of a contoured surface. In the composite blades for the 1979 and 1985 engines, there could be 400 different shaped layers or laminae plies of material needed to completely define the fan blade configuration and fewer layers for the booster blades since they are smaller blades. This general description of the composite blades seems complex, but the basic concept in defining compound shapes by layers of varying shapes is a common approach that has been employed for several decades. However, modern day technology can simplify the method of accomplishing this rapidly, precisely, and repetitively. The concept best suited to the manufacture of the blades by the lamination process is by molding the stacked laminae (preforms) in a heated match metal mold under pressure delivered by a hydraulic press equipped with programable instrumentation to control time, temperature, and pressure parameters.

Figure 25 shows the process pictorially and in the sequence that has been used to manufacture several hundred large polymer composite blades. Figure 26 illustrates how these blades can be made in production quantities of more than 10,000 blades. This can be accomplished by the use of special material handling and multi-clicker die equipment to precut lofted patterns as shown in Figures 27, 28 and 29. These patterns are conveyed to a sorting area where subassemblies of the patterns are made, then conveyed to a station where these subassemblies are stacked in succession to make a preform (Figure 30). On completion, the blade preforms are placed into a heated match metal die (Figure 31) and molded under pressure by use of a hydraulic press equipped with programming devices to control time, temperature, and pressure parameters.

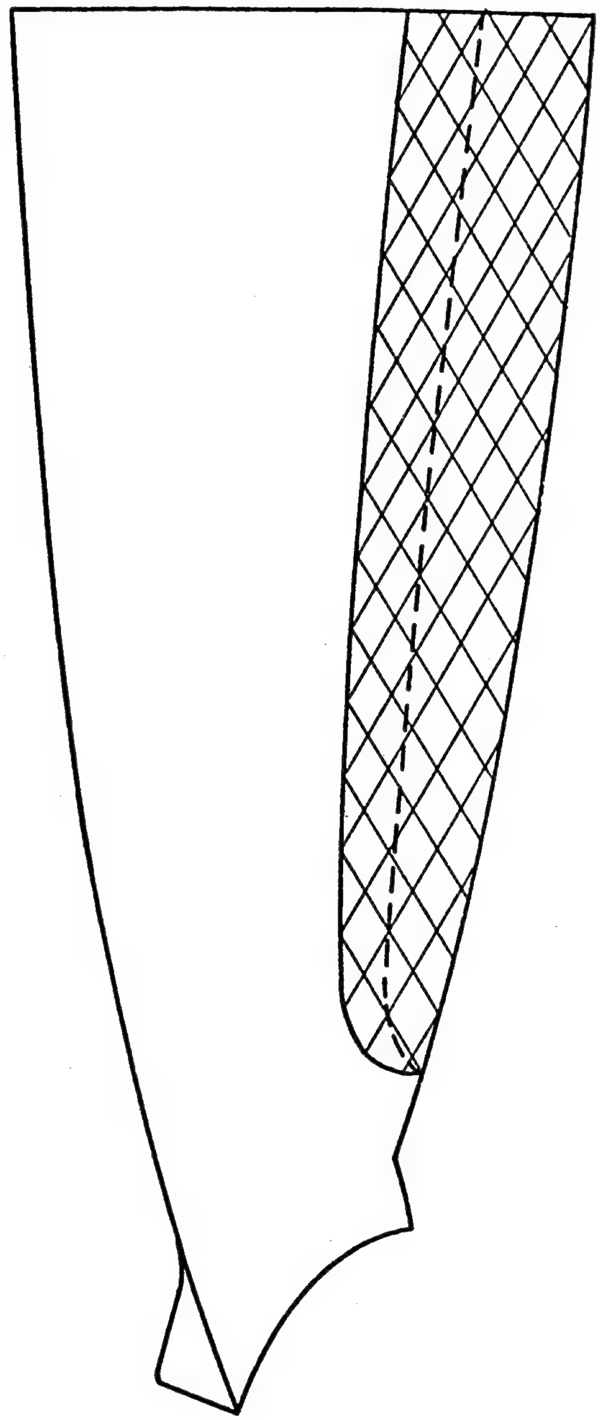


Figure 24. Polymeric Composite Blade.

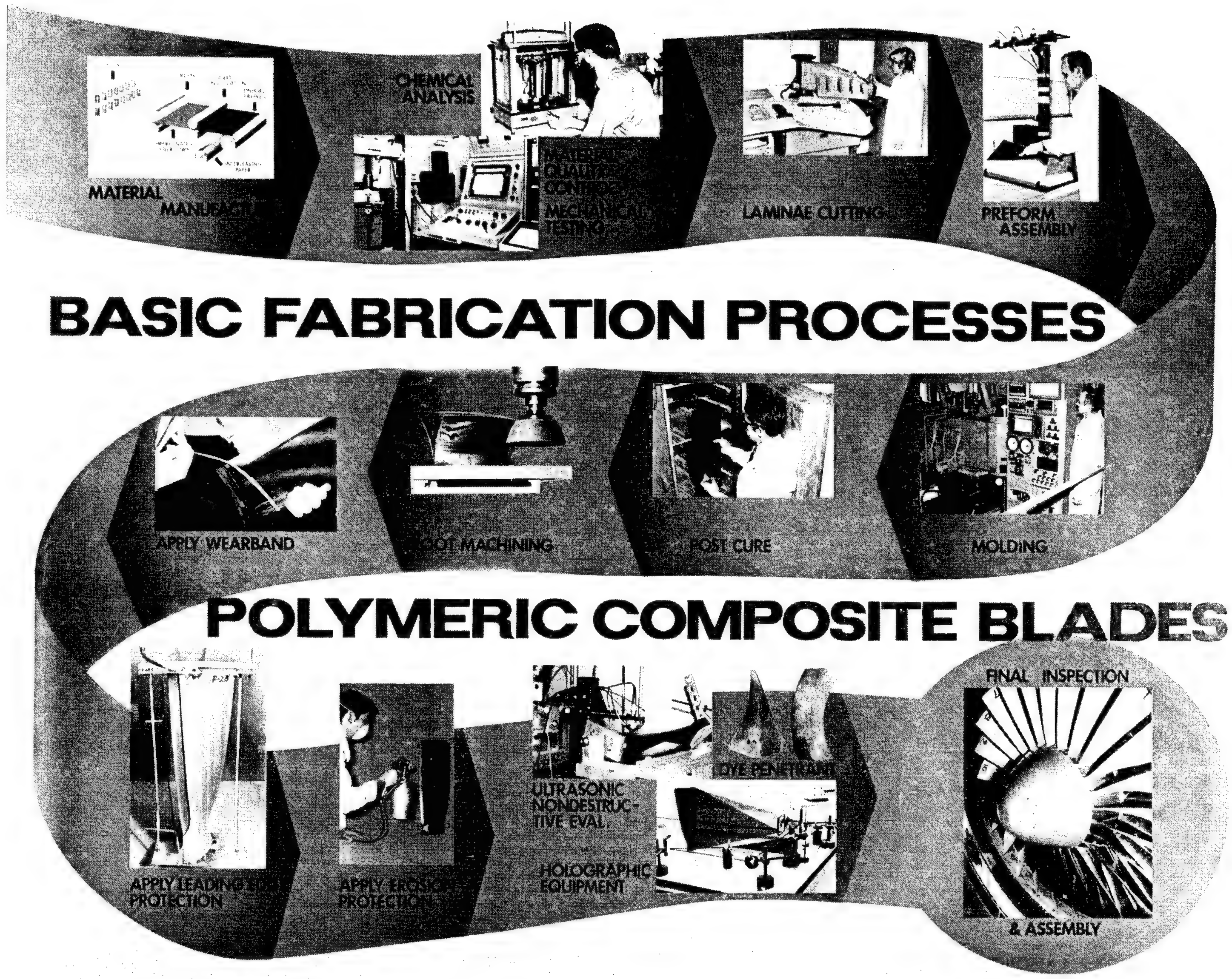


Figure 25. Basic Fabrication Processes for Polymeric Composite Blades.

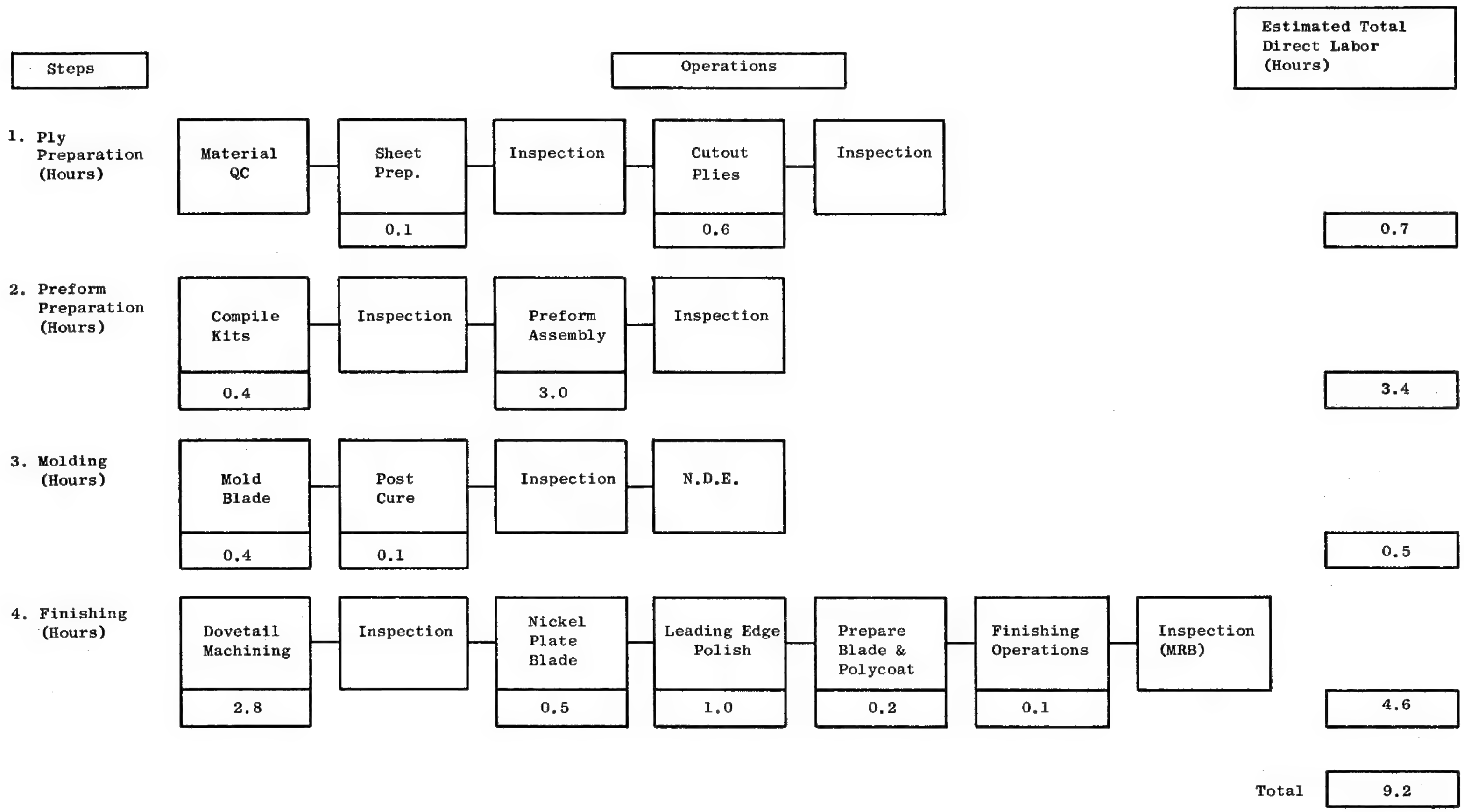


Figure 26. Polymeric Composite Blade, Unit Labor Hours @ 10,000th Blade.

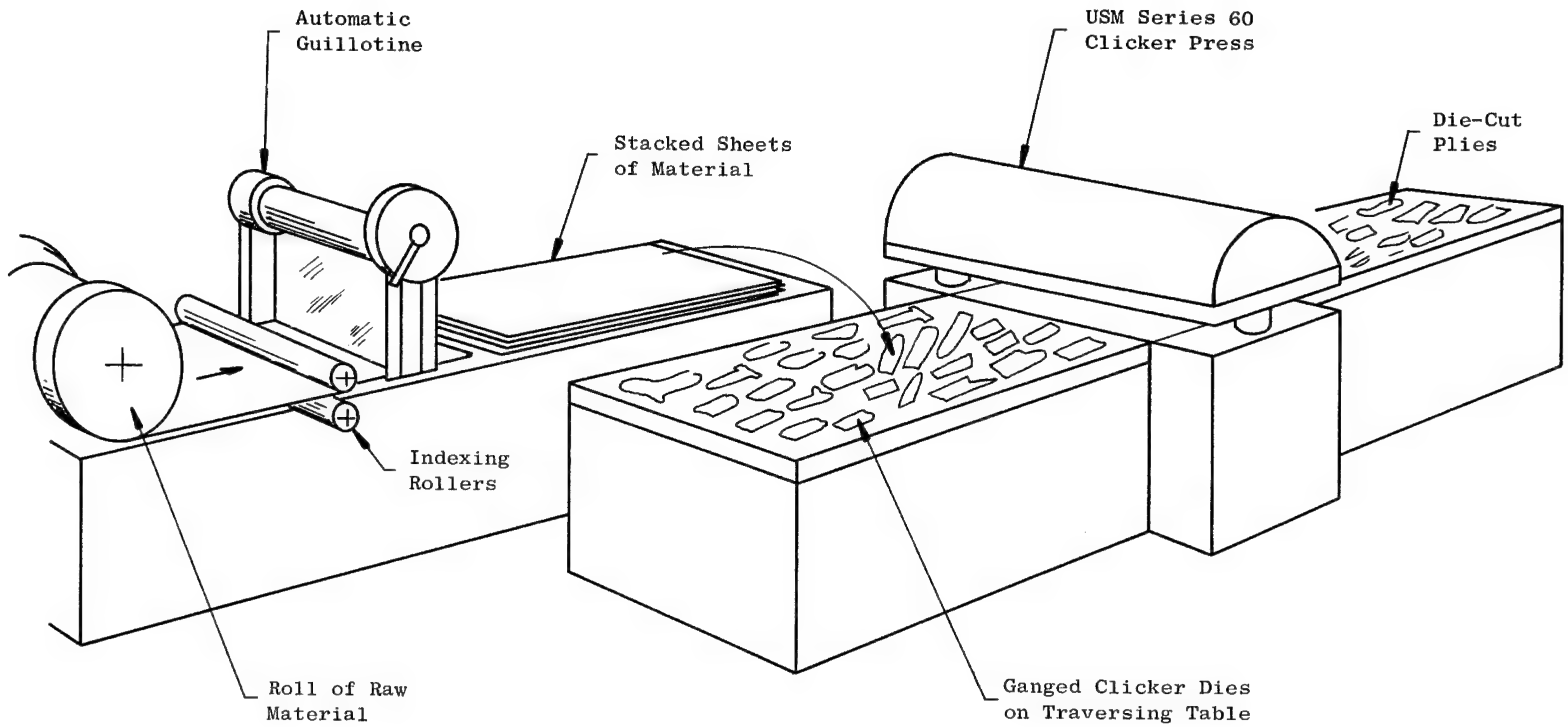


Figure 27. Semiautomated Ply Generation Technique for Polymeric Composite Blade Production.

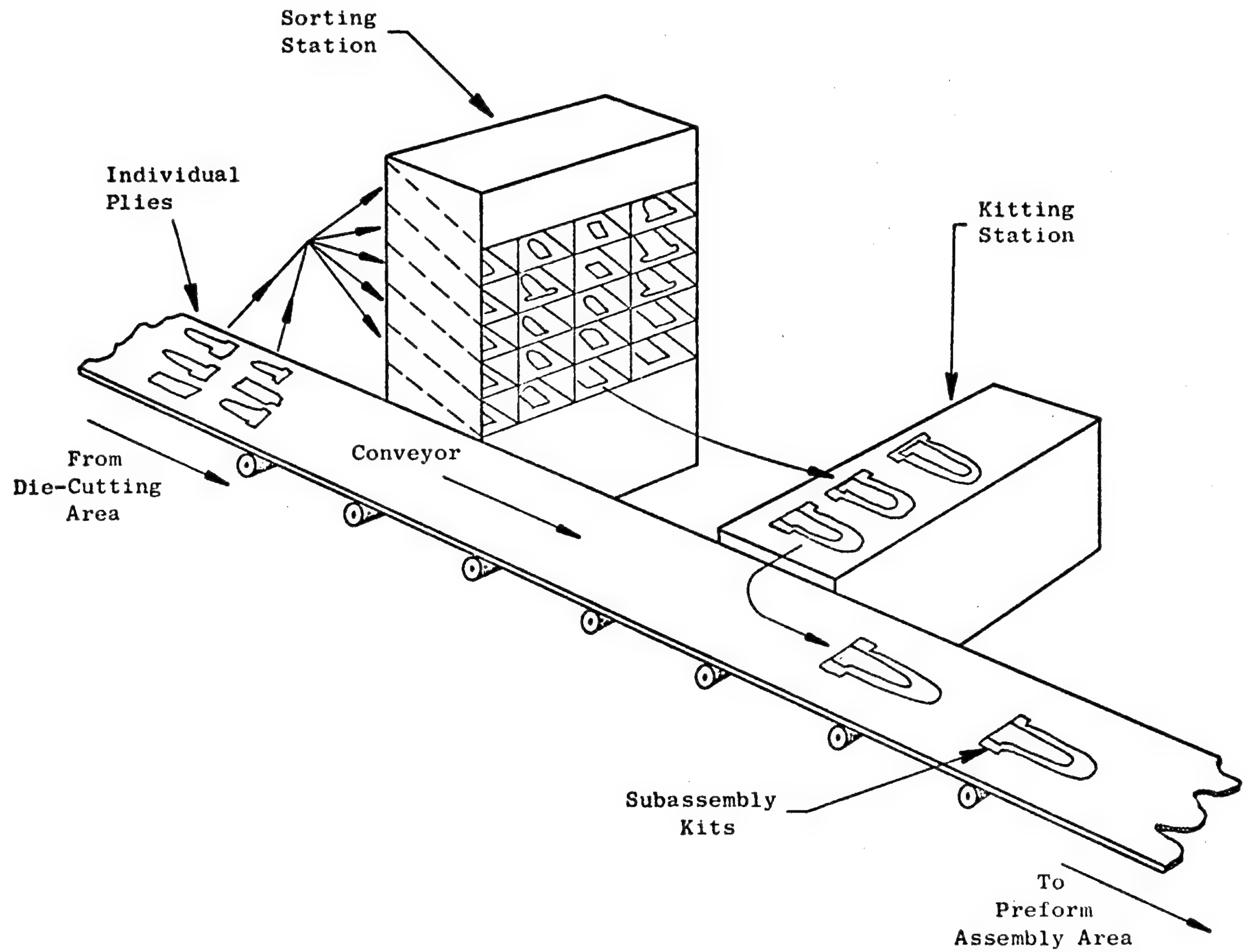


Figure 28. Typical Sorting and Kitting Operation, Polymeric Composite Blade Production.

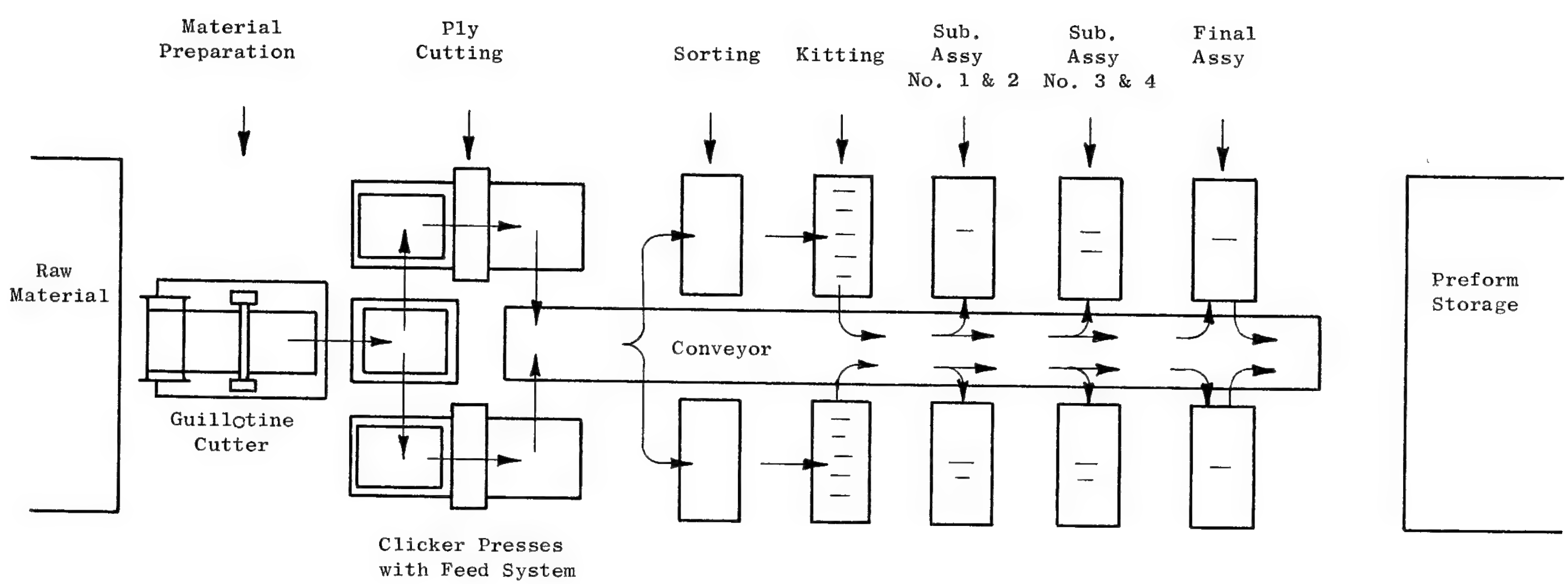


Figure 29. Typical Layout of Ply Production and Preform Area.

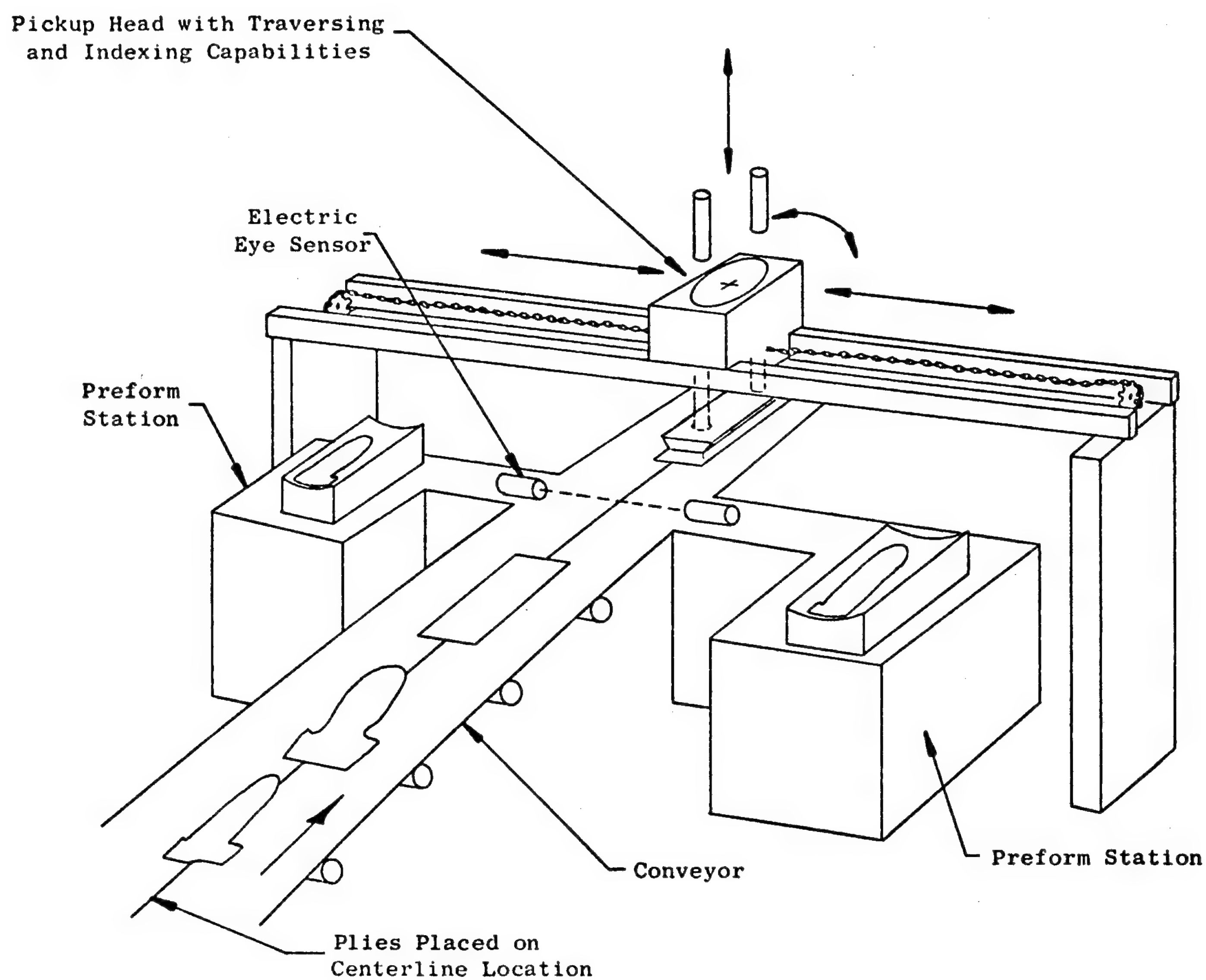


Figure 30. Automatic Blade Preform Stacking Process.

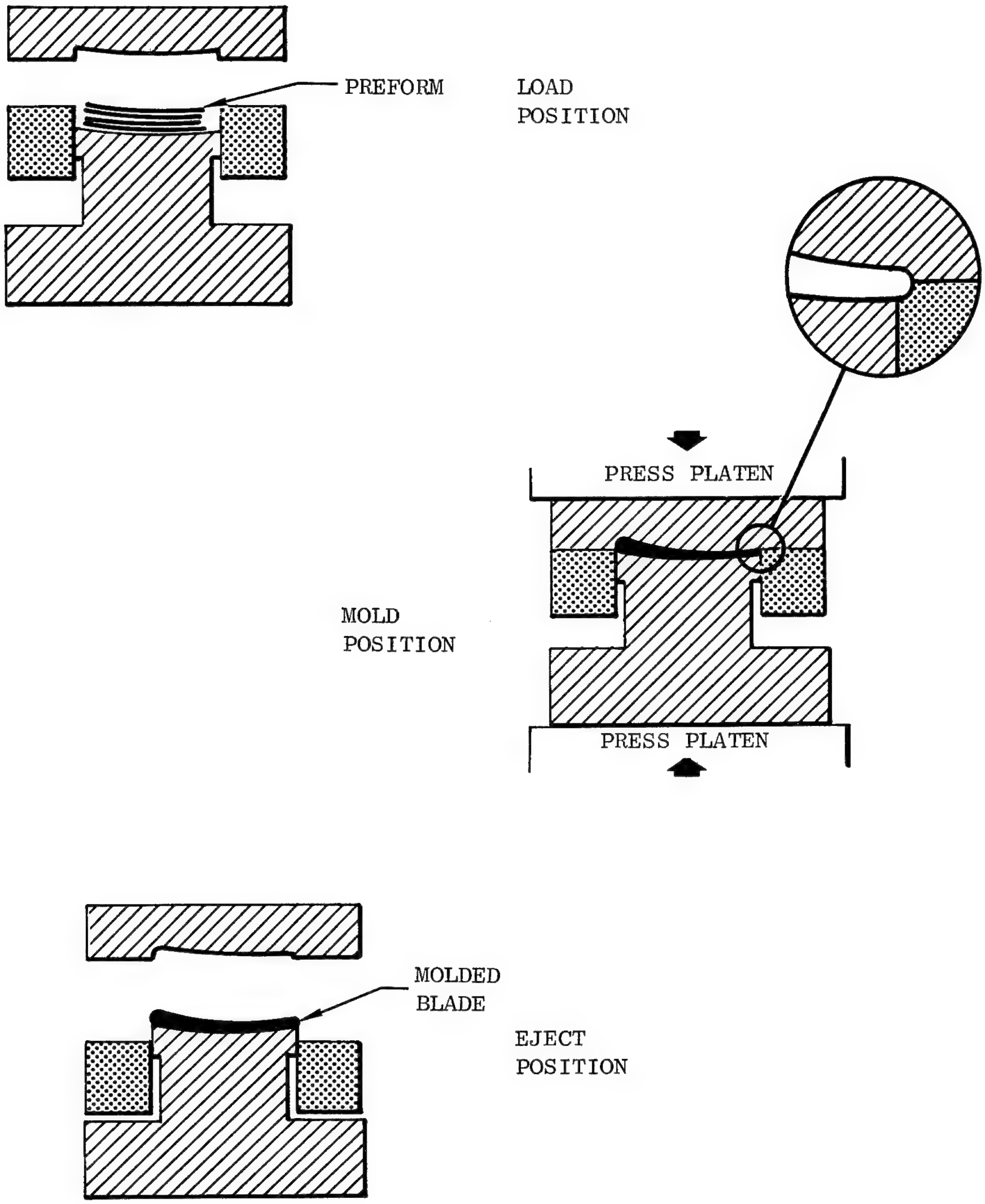


Figure 31. Composite Blade Mold Tool Design.

This process completes the first phase of the cure in molding the blade. When cure of the blade is complete, it is removed from the press, post cured, and conveyed to a station where the dovetail is machined (Figure 32) to engineering requirements. Then the blade is scheduled to an area where a protective coating is applied. This is the final step in the process and the blade is now ready to be inspected.

This entire process utilizes standard assembly line techniques and equipment which have been modified to meet the unique composite construction of the polymer composite blade.

3.4.2 Nacelle - 1979

The nacelle design is composed of several major segments to make one large-diameter, long duct. Each major segment consists of an assembly of polymeric composite parts which have been adhesively bonded and/or bolted together. The sound suppression features are part of the nacelle structure and the construction is made with fiber reinforced polymeric skins that are adhesively bonded to a suitable core. This is a general description of the nacelle designs for 1979 and 1985. However, each differs in construction and will require a different approach to their manufacture.

Specifically, the 1979 engine nacelle design (Figure 33) has a construction consisting of honeycomb sandwich panels attached to polymeric composite rib structures that are located radially and axially for internal airflow surfaces. The sound suppression panels with porous airflow skins are mechanically attached to the rib structures at the internal surface of the nacelle. External surfaces consist of solid laminate panels of fiber reinforced polymeric composite materials that are adhesively bonded and/or mechanically affixed to the radial and axial rib structure.

The fabrication sequence that would be used in manufacture of any major segment of the nacelle is shown in Figure 34. The type of tooling that would be used in manufacture of these components and assemblies is described below.

Nacelle Internal Panel Fabrication

Male dies would be used for molding all acoustically treated sandwich panels that fit to the internal airflow surface of the nacelle. These male dies would have the capability to mold a fiber reinforced polymeric laminated airflow face sheet with controlled porosity. The face sheet and back sheet would be molded with the

honeycomb in place by a unique co-cure process. This process consists of curing the entire sandwich construction at one time with vacuum bag/autoclave technology at specified times, temperatures, and pressures. The attached sketch (see Figure 35) is a simplified illustration of the male die process concept where the vacuum bag/ autoclave technique is used.

Nacelle External Panel Fabrication Concept

Female type dies and vacuum bag/autoclave technology would be used to manufacture the fiber reinforced polymeric skins for the panels of the external surface of the nacelle. These panels will also be processed at specified time, temperature, and pressure parameters.

Ribs and Brackets Fabrication

Graphite fiber reinforced polymeric composite radial and axial rib structures and brackets for joining external panels and internal panels to the rib structures would be manufactured on match metal dies. These components would be processed in a press at temperature and pressure for a specified time.

Assembly of Nacelle Segment

Trim and drill fixtures would be used in machining the autoclaved components to design requirements. These components, the parts that have been molded to size, and the necessary metal components would be assembled with the aid of an assembly fixture that holds each component in position during the bonding and installation of mechanical fasteners.

3.4.3 Nacelle - 1985

The 1985 engine nacelle design is composed of several major segments that are assembled to make one large duct. Each segment is defined as a unitized sandwich construction. It consists of a two-phase, full-depth, honeycomb core material with co-cured fiber reinforced polymeric composite facings. Sound suppression treatment is integral with the full-depth sandwich construction for the total internal airflow surface of the nacelle. Additionally, the inlet splitter and supporting struts are a sandwich construction with fiber reinforced polymeric composite laminate faces that have a controlled porosity structure as part of the sound suppresssion treatment. This construction is common to both airflow surfaces of the splitter and support structure.

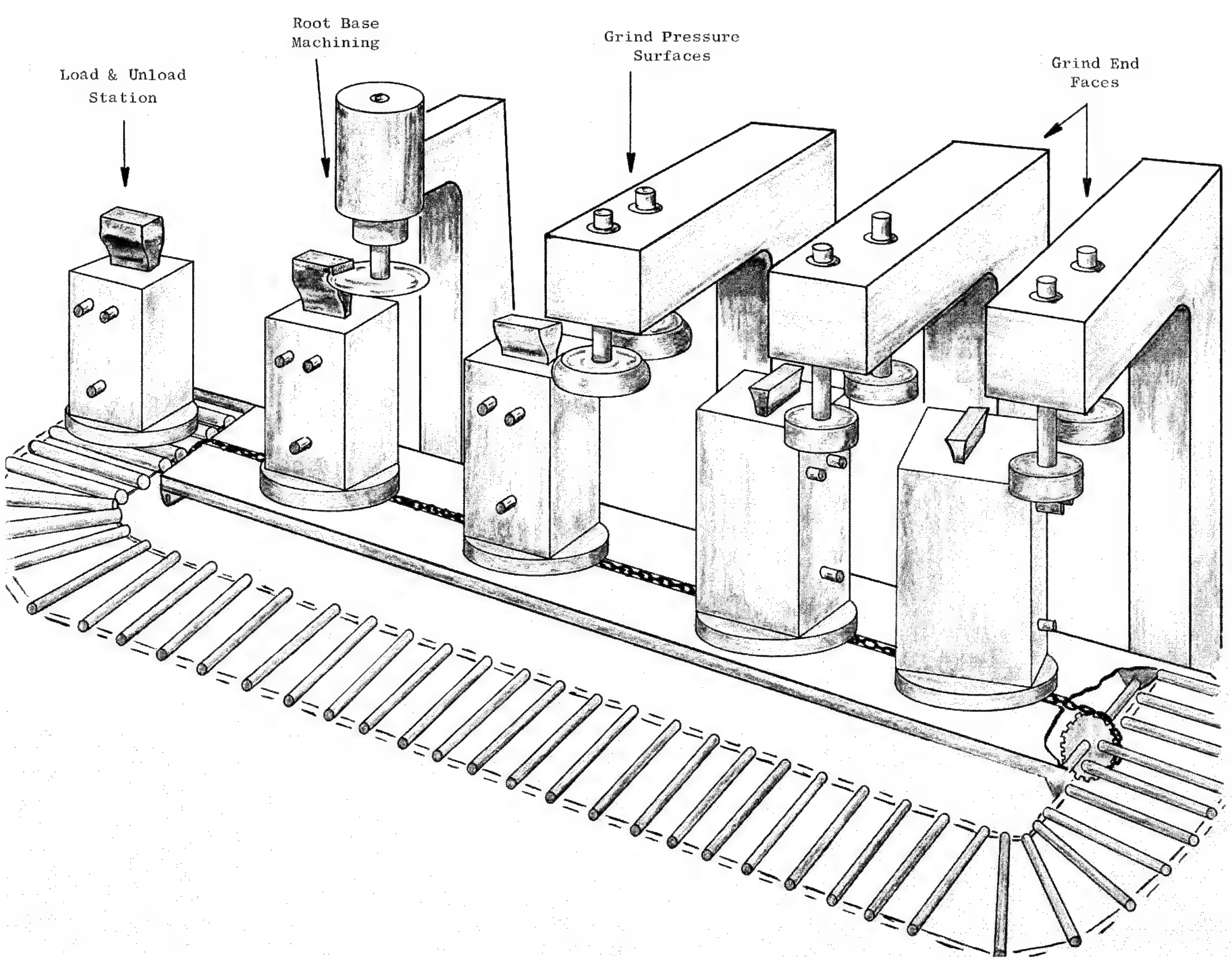


Figure 32. Automated Machining of Dovetail Root, Polymeric Composite Blade Production.

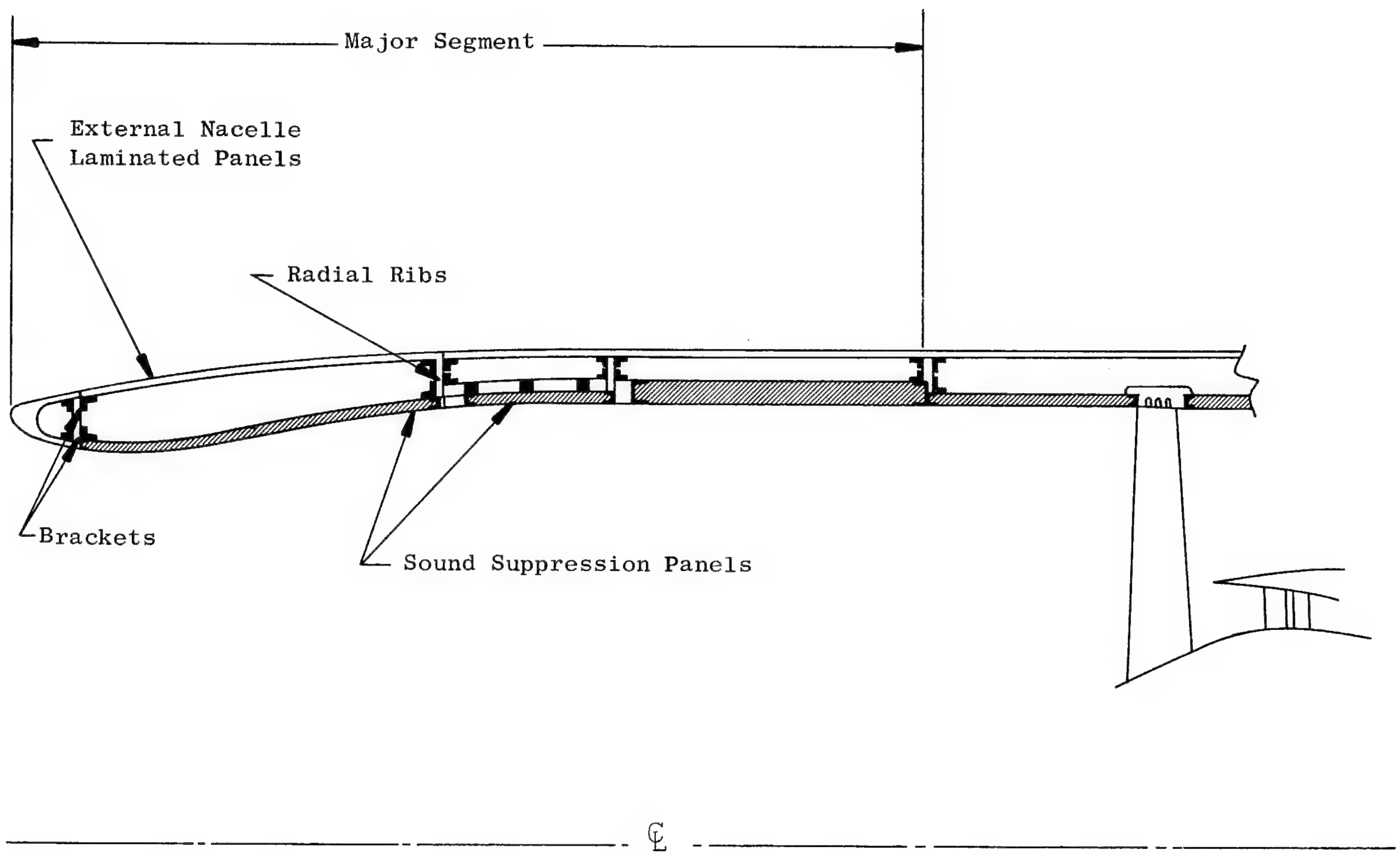


Figure 33. 1979 Engine Inlet Acoustic Design.

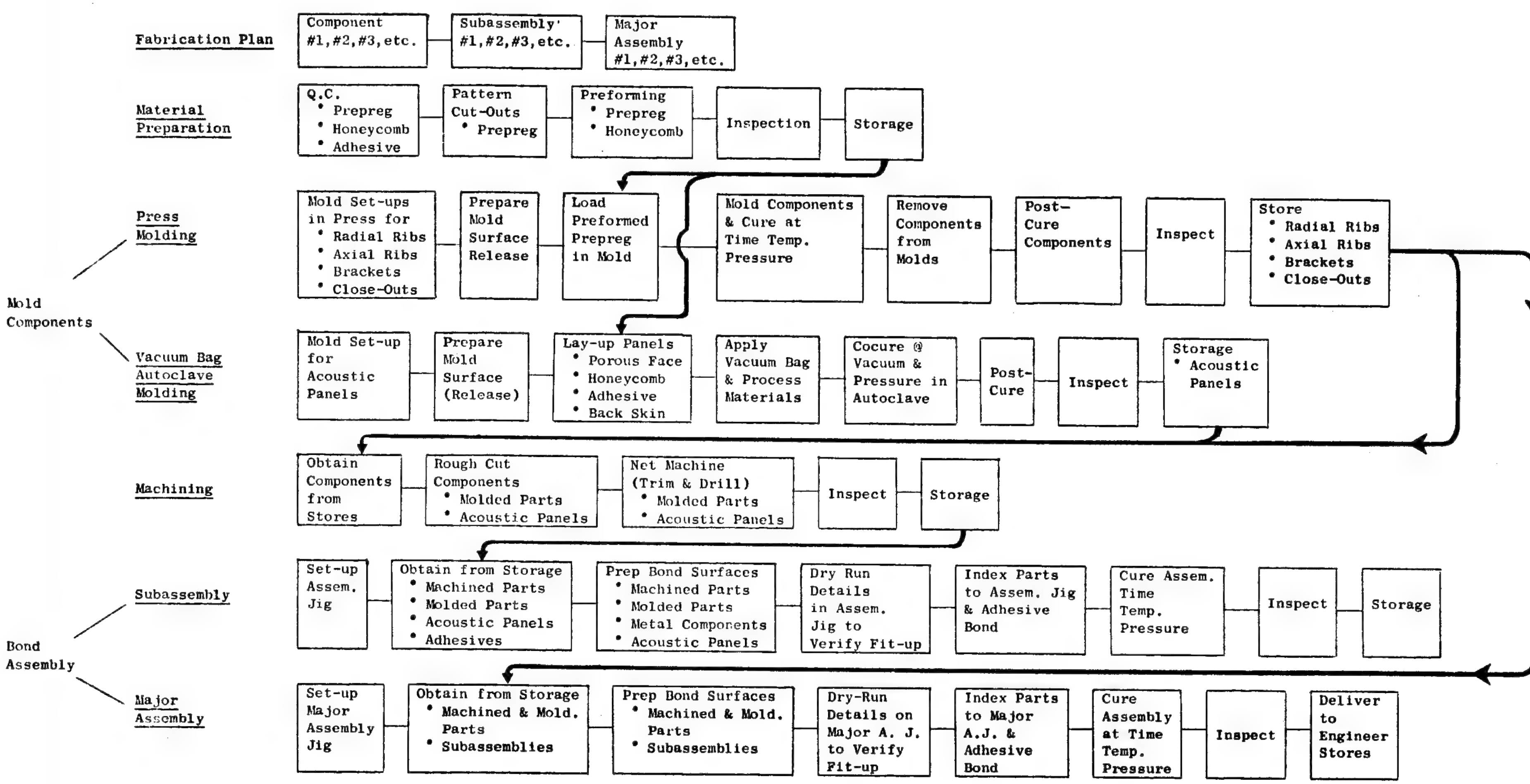


Figure 34. Fabrication Sequence for Typical Polymeric Composite Segment of the 1979 Nacelle.

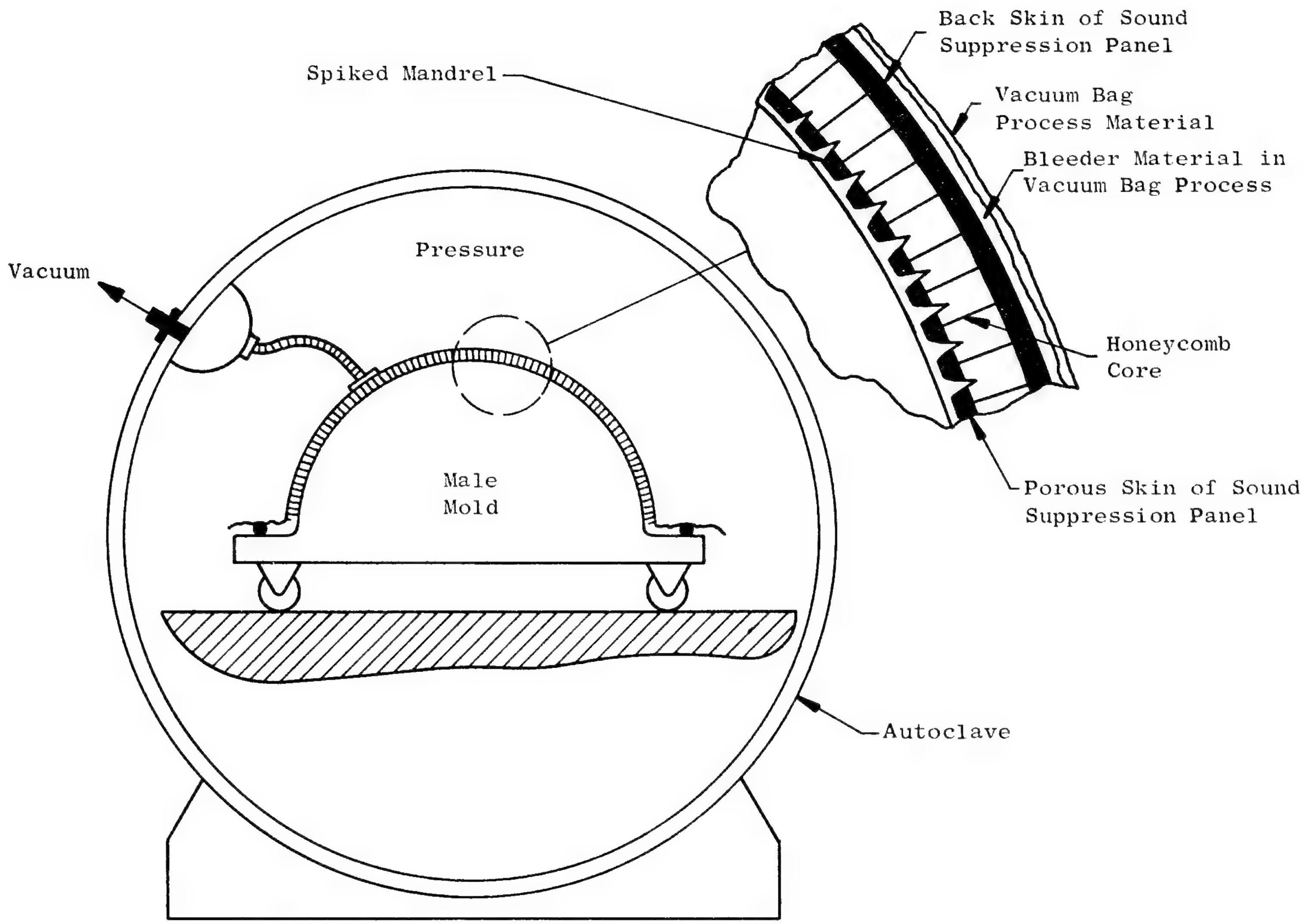


Figure 35. Male Mole Process Concept, Acoustic Panel, 1979.

The basic fabrication methods for the manufacture of a typical major segment (see Figure 36) of the nacelle would consider the use of the following types of process methods.

- Vacuum bag/autoclave process techniques with full definition of time, temperature, and pressure parameters during cure of the polymeric composites. This technique would be used when processing on male or female type molds. Male molds would be used in the manufacture of outer duct airflow surface construction. Female molds would be used for core cowl (inner duct) airflow surfaces.

- Match metal die molding processes would be used for ribs, panel closeout rings, and strut leading and trailing edge details. These dies would be used in a hydraulic press with heated plattens and sufficient controls to program closing speeds, temperatures, and pressures at specified time periods.

- Machining fixtures for trim, drill, routing, milling and form operations would be used to rough machine and finish machine components made with the vacuum bag and match metal die manufacturing methods and for shaping honeycomb core material for the full-depth core construction.

- Finished molded and machined polymeric composites would be brought together first in subassemblies, then as a major assembly. This would be accomplished by subassembly and major assembly jigs.

The fabrication concept to be considered in the manufacture of the major segments of the nacelle consists of utilizing standard vacuum bag/autoclave technology methods. The two-phase, full-depth, unitized honeycomb structure (Figure 37) integrates the acoustic treatment with the full-depth structural honeycomb and would be made by those processing techniques (Figure 38). The structural honeycomb has a different cross-sectional shape than the acoustic honeycomb but each must mate at the acoustic cell close-out interface. This would be accomplished by machining the honeycomb segments to shape. The honeycomb can be machining in the unexpanded or in the expanded condition. After machining the different shapes, the honeycomb would be primed with a corrosion resistant coating, then formed to a specific shape with special tooling to meet the nacelle contour requirements.

These formed and shaped segments of the honeycomb, with their related face sheets, would be built upon a mold in the following sequence.

NACELLE FABRICATION SEQUENCE

Sequence No.

1. MOLD PERFORATED FACE SHEET

Lay down fiber reinforced polymeric composite prepreg material over released spiked mandrels. See Figure 38.

↓

2. INSTALL ACOUSTIC HONEYCOMB

Place preformed acoustic honeycomb over the prepreg. Add shear material at honeycomb joints.

↓

3. CURE

Vacuum bag and cure at temperature, pressure and time in autoclave. After cure, remove process materials.

↓

4. APPLY ACOUSTIC CLOSE-OUT MATERIAL

Lay up the acoustic close-out material over the acoustic honeycomb.

↓

5. ADD STRUCTURAL HONEYCOMB

Place the preformed structural honeycomb on the uncured acoustic close-out material. Add shear tie material at honeycomb joints.

↓

6. CURE

Repeat step #3.

↓

Sequence No.

7. ADHESIVE FILM

Place uncured adhesive film over the structural honeycomb and metal components.

8. OUTER SKIN, RIBS, BRACKETS, CLOSE-OUTS

- Mold outer skin with fiber reinforced polymeric composite material using vacuum bag/autoclave technology at a specified temperature, pressure, and time schedule. Prepare cured laminate for bonding.
- Mold ribs, brackets, and close-outs with advanced composite materials using match metal die/press technology and cure at a specified temperature, pressure, and time schedule. Then prepare bonding surface for bonding.

9. APPLY OUTER SKIN, RIBS, BRACKETS, & CLOSE-OUTS

Position precured and rough trimmed outer skin over the honeycomb and advanced composite ribs and close-outs that have adhesive film applied to their bonding surfaces.

10. CURE

Repeat step #3, then remove cured subassembly from mold.

11. INSPECT

Inspect construction for adhesive bond integrity.

Sequence No.

12. MACHINE

Trim/drill subassembly and prepare for installing into major assembly jig.

↓

13. MAJOR ASSEMBLY

Install subassemblies — two nacelle halves of one major segment. See Figure 39. Fit up the two subassemblies. Trim/drill as required for mate to adjoining components. Adhesive bond two halves with doubler joint. Adhesive bond mating metal components.

↓

14. CURE

Process major assembly to step #3 schedule.

↓

15. CLEAN UP AND COAT

Clean up major assembly and coat with required protective coating material.

↓

16. INSPECT

Ship to final inspection and inspect.

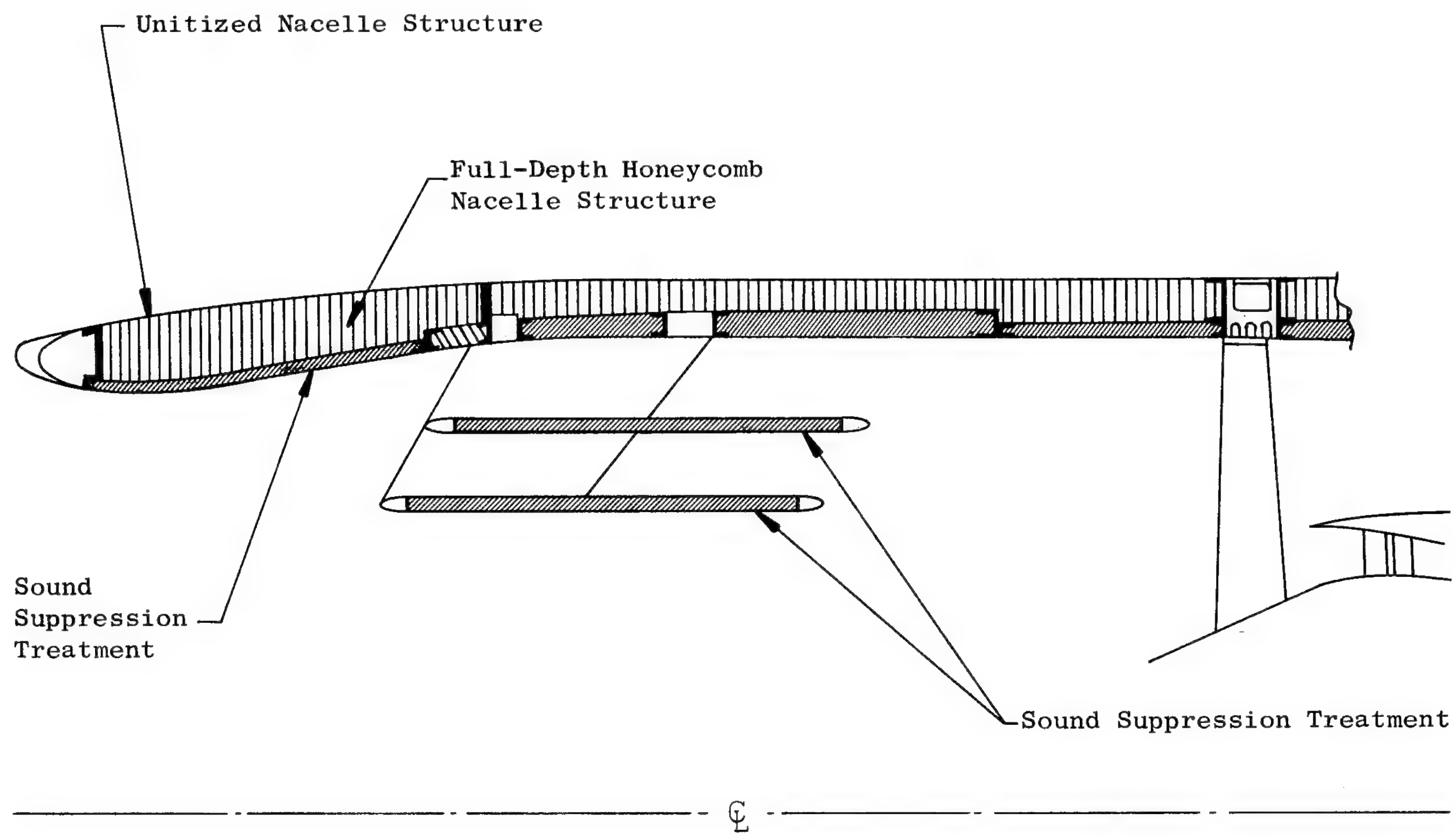


Figure 36. 1985 Engine Acoustic Design.

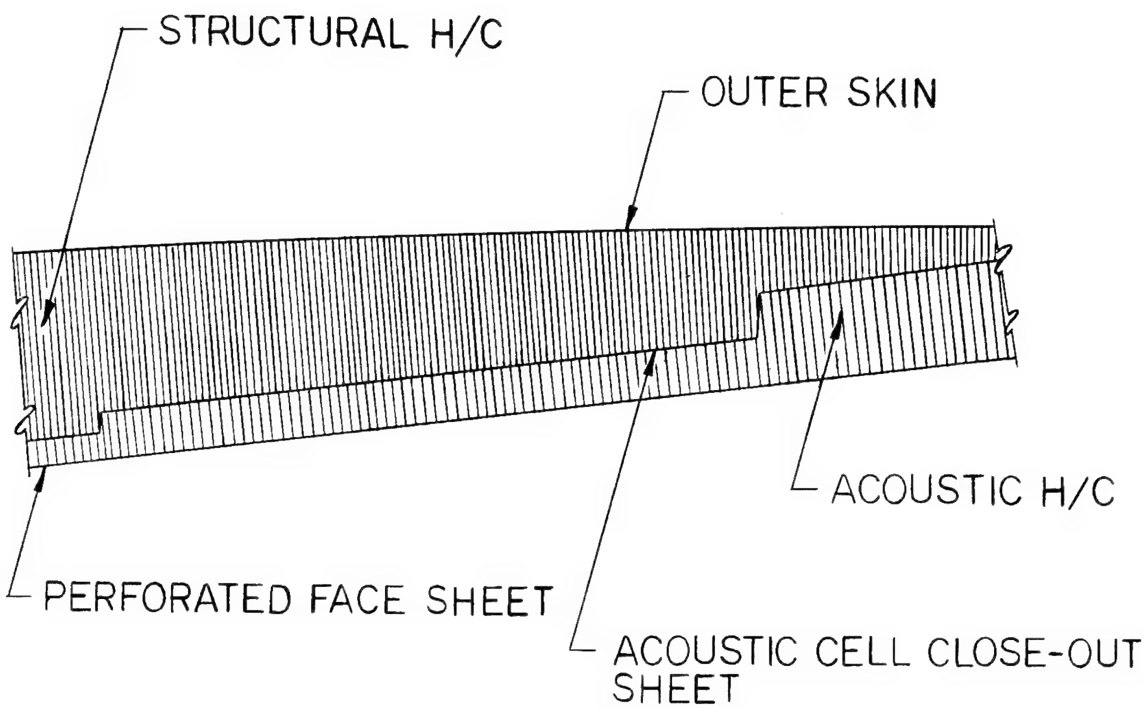


Figure 37. Two-Phase, Full-Depth, Unitized Honeycomb Structure with Integrated Sound Suppression Construction.

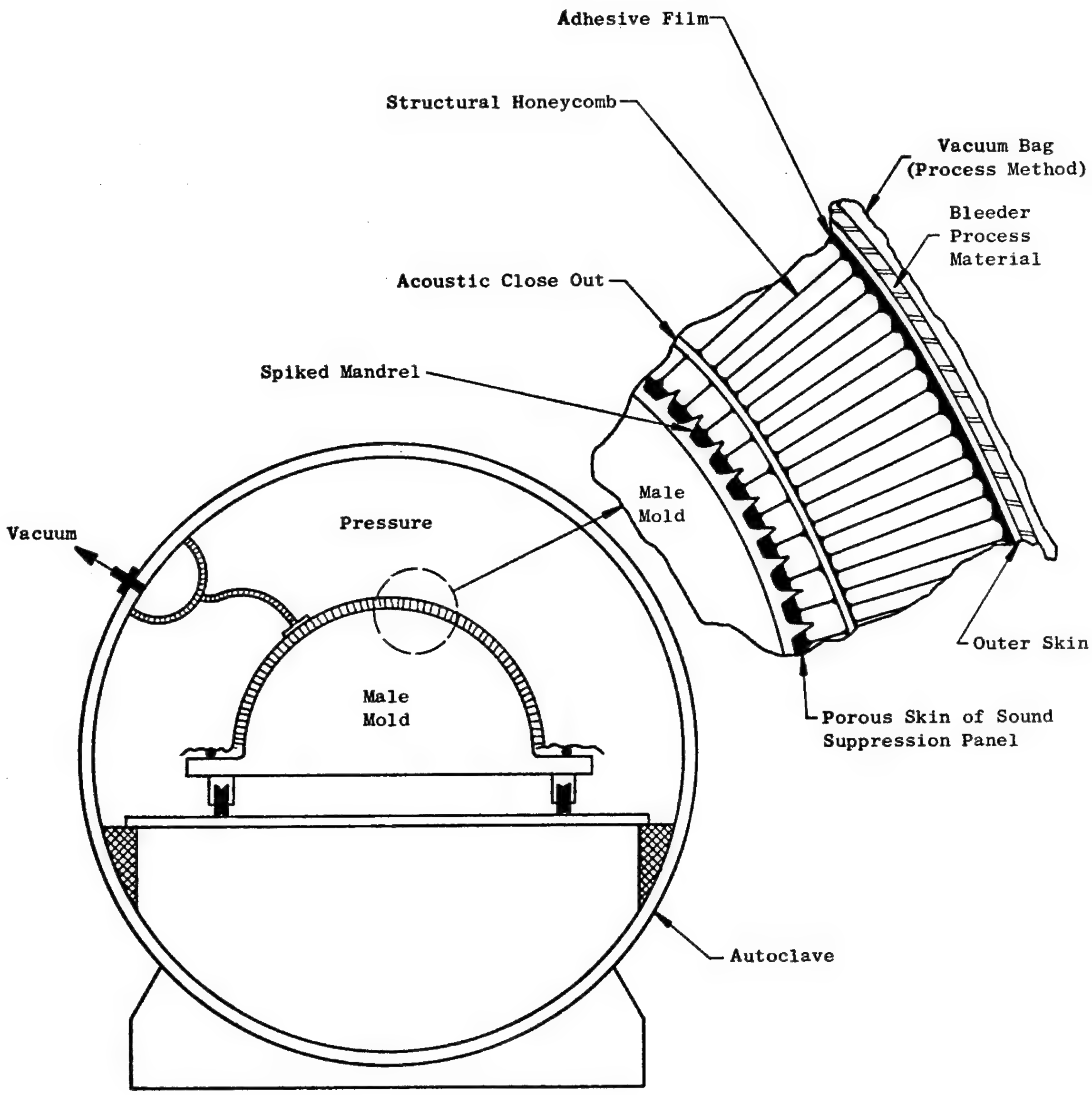


Figure 38. Male Mold Process Concept Acoustic Panel, 1985.

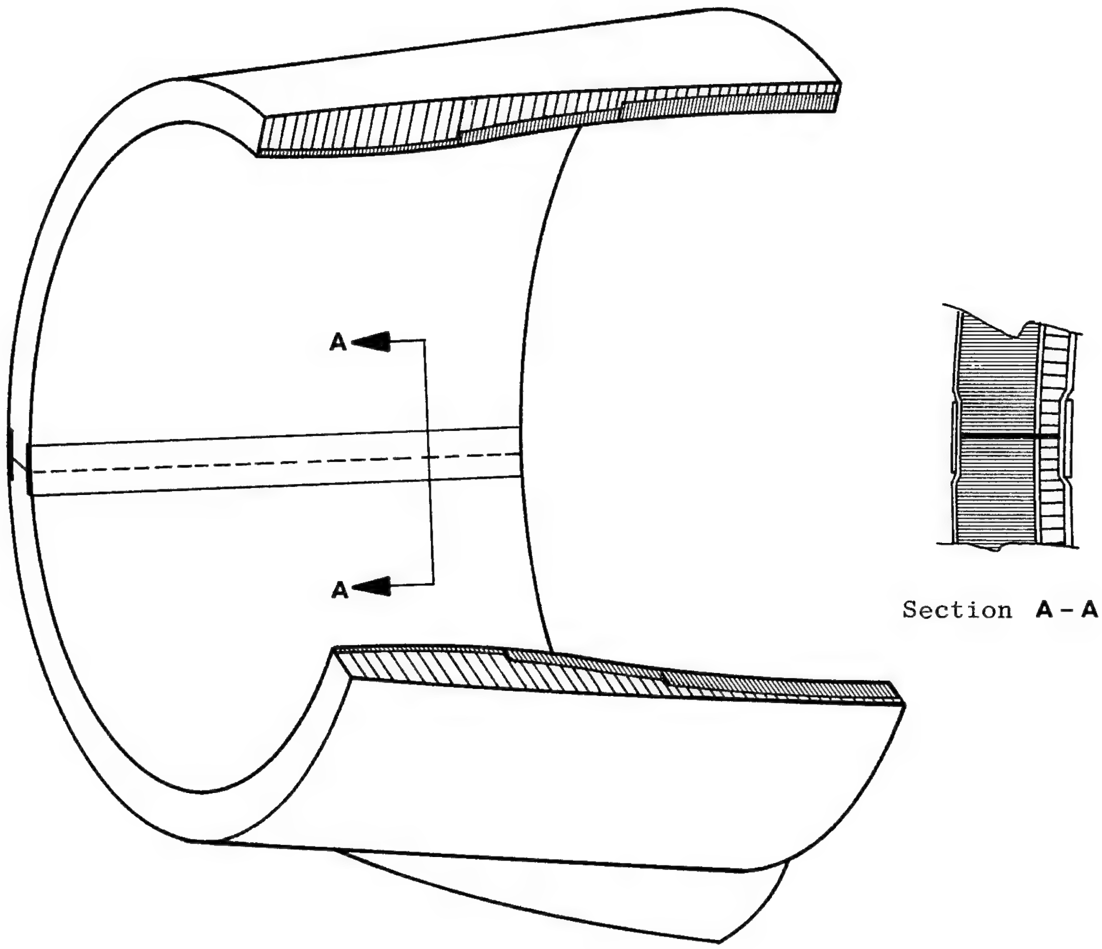


Figure 39. Major Segment of 1985 Nacelle Assembly of Halves.

The above sequence of fabrication is a generalized version of the method of manufacturing a typical segment of the nacelle. Except for configuration changes in design and minor variations in sequence of manufacture, this concept would be used throughout the manufacture of the other segments of the nacelle. Wherever possible, the co-cure concept would be used to gain the added payoff of low cost processing methods.

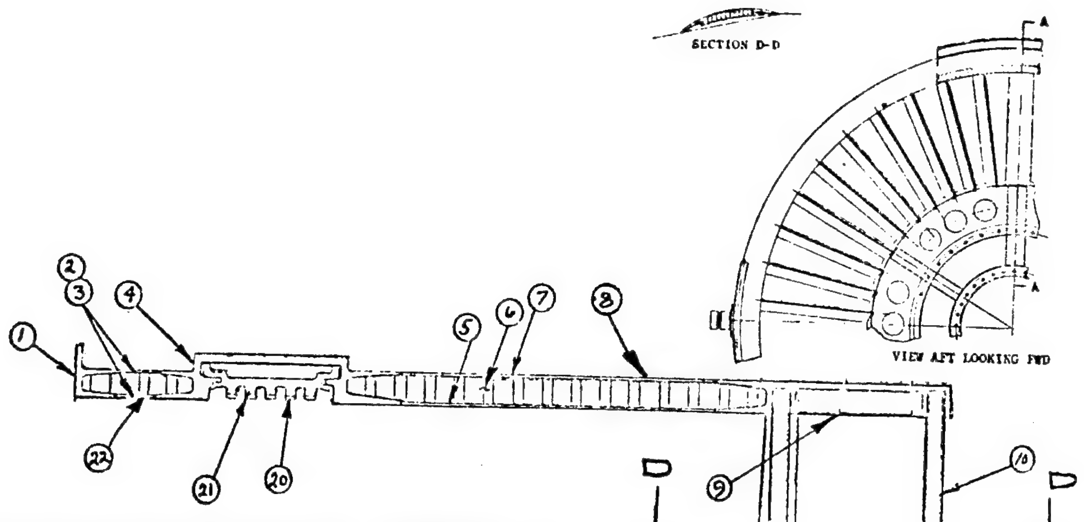
3.4.4 Fan Frame

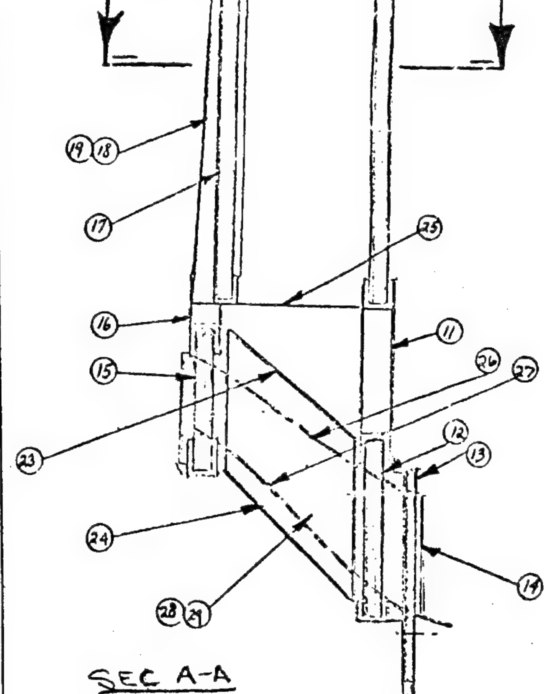
The main features of the frame include several spoked structural graphite/polymer wheels spaced axially with graphite/polymer airfoil skins and flowpath components adhesively bonded within the spoke and ring regions (Figure 40). These spoked wheels with outer and inner rings are attached to the outer casing sandwich structure immediately over and directly aft of the fan blades. This entire frame structure is a bonded assembly consisting of laminates and sandwich construction.

Fabrication details considered in the manufacture of the frame are as follows:

- Fabrication outline plan
- Materials preparation
- Press molding techniques using matched metal molds and hydraulic press
- Vacuum bag/autoclave techniques using male and female tooling
- Machining methods - trim/drill fixtures for trimming and drilling molded parts and assemblies of molded components
- Bond assembly technology - subassembly and major assembly jigs for maintaining configuration tolerances during the adhesive bonding process.
- Inspection

The above process methods and general sequence in the manufacture of the polymeric composite frame construction is illustrated in Figure 41. This sequence of events would apply to the 1979 or 1985 version of the frame.





ITEM	COMPONENT NAME	PROCESS METHODS
1	Filmold Flange	MD, AB
2	Outer Skin	VA, M, AB
3	Inner Skin	VA, M, AB
4	Double Filmold Flange	MD, AB
5	Inner Skin	VA, AB
6	Honeycomb	M, AB
7	Outer Skin	VA, M, AB
8	Filmold Flange Ring	MD, AB
9	Skin	MD, AB
10 - 14	Aft Wheel	MD, AB
15 - 17	Front Wheel	MD, AB
18	Concave Skin	MD, M, AB
19	Convex Skin	MD, M, AB
20	Seal	M, AB
21	Shroud Metal	M, AB
22	Honeycomb	VA, M, AB
23	Skin - Cone	VA, M, AB
24	Skin - Cone	VA, M, AB
25	Skin - Cylinder	MD, M, AB
26	Skin - Flow Path	VA, M, AB
27	Skin - Flow Path	VA, M, AB
28	Concave Skin	VA, M, AB
29	Convex Skin	VA, M, AB

AB = Adhesive Bonding
MD = Match Metal Die
VA = Vacuum Bag/Autoclave
M = Machining (Trim, Drill)

Figure 40. Vane Frame, Composite (1985).

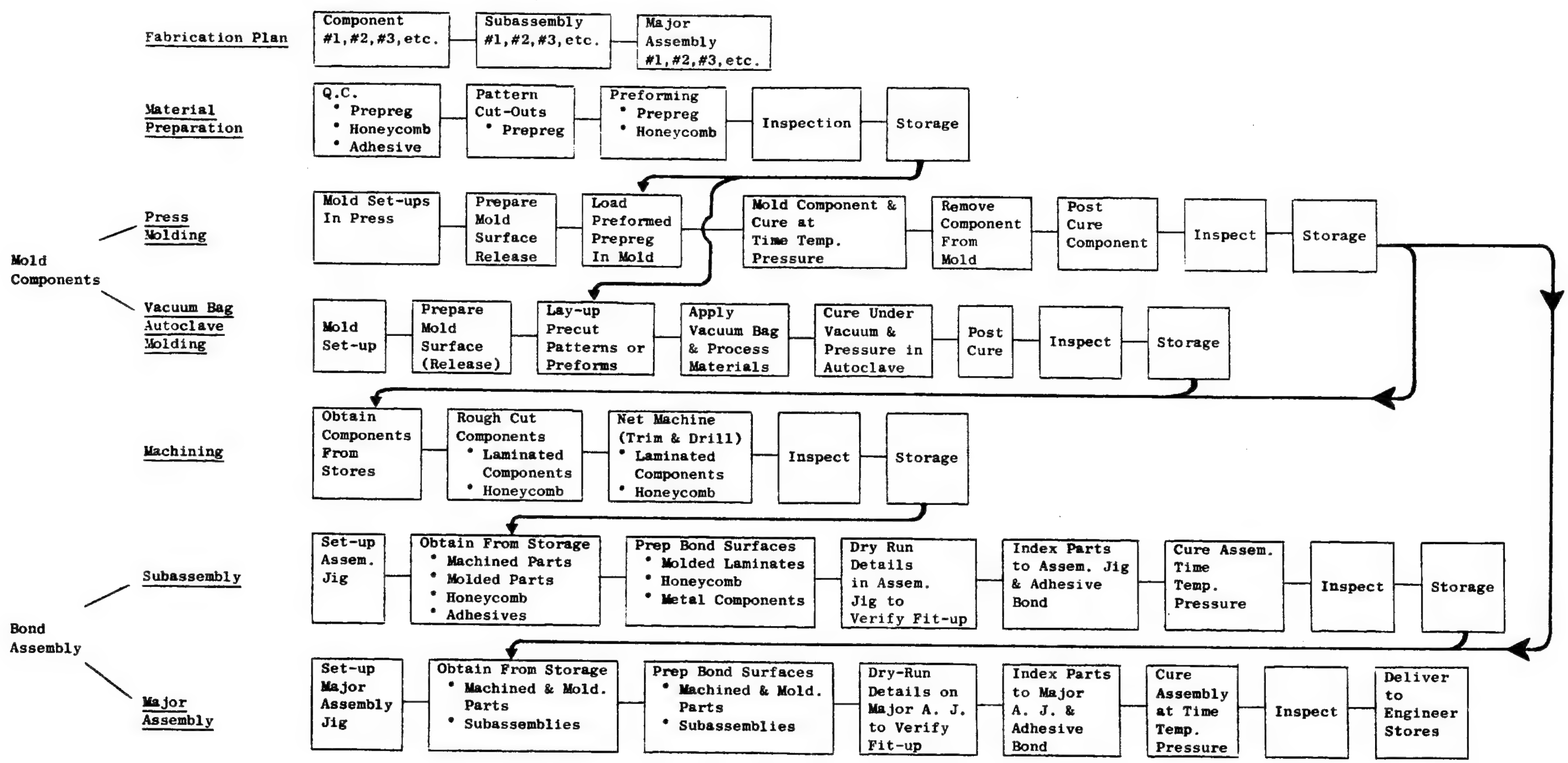


Figure 41. Fabrication Sequence, Polymeric Composite Frame

3.5 COMPONENT COST ESTIMATES

This section discusses the methods used to develop both the production costs of the components described in Section 3.3 and the development costs necessary to attain the technology necessary to successfully design and fabricate these components. Estimated man-hours and direct costs are given for each component and the average cost of the 600 units is given as a percentage of the metal baseline component cost except for the turbine blades for which a range of costs are given. The metal component cost, insofar as was practical, was taken from actual cost on production engines. The detail cost data is presented for the actual size of the component as designed and compared to an equivalent sized metal component. In order to make the best use of existing data, these component sizes were not necessarily the exact size as required for the baseline engine. There were no major size discrepancies; but in order to provide a coherent summary, components and their costs were scaled to a common thrust size engine for the DOC and ROI investigations. This size discrepancy was not sufficient to affect the development parameters.

3.5.1 Cost Estimating Procedure

The outline of the component cost estimating and evaluation procedures used in this benefit analysis study consisted of the following five steps:

1) Cost Estimating - Development
2) Cost Estimating - Production
3) Comparative Analysis - Development
4) Comparative Analysis - Production
5) Percent Comparative Analysis Summary

Steps 1 and 2 were derived by listing all candidate engine composite components individually and describing them in detail together with all the parameters affecting their respective related man-hours or direct costs. Steps 3 and 4 compiled similar costs of relative development and production parameters of the proposed advanced turbofan engines together with existing or projected costs of the 100 percent baseline engine components. Step 5 is a final summarization of all the data generated for easy comparison between current and proposed future technology costs and payoff effects on both engines and aircraft.

Each category of cost estimating and comparison relationships and some of the rationale behind subsequent estimations and calculations are presented below.

In order to generate realistic input for data summary, a series of cost estimating and comparative analysis were generated to delineate all aspects of effort and relationships necessary to support experienced judgement of man-hours and direct costs for the many parameters listed for each proposed composite engine component.

Historically, the substitution of composites for metals has demonstrated significant payoff in both cost and weight, but in some cases, maximum payoff has been inhibited by the requirement of direct substitution of composite geometry for metal geometry in order to keep the cost of such substitution to a minimum. By initiating the proposed turbofan engine designs with the use of composite material considerations wherever feasible, a significant improvement in composite structure efficiency was often manifest in the final engine structure.

3.5.2 Production Cost Estimations

Production manufacturing cost estimations have been made with the guidance of Value Process Engineering who are responsible for estimating costs of composite production hardware for production at the GE-Albuquerque Plastics Facility. In arriving at the average cost for the 600 units, the following considerations were given attention:

Materials

1) Material cost per unit
   - Raw material
   - Metal hardware
   - Coatings
   - Adhesives/primers
2) Waste and spoilage add 10% to cost
3) Unreported losses per unit add 12% to cost
4) Expense of material procurement/unit add 7.1% to cost

Labor

1) Production setup/checkout cost/unit
2) Time to manufacture component or assemble
3) Cost for overrun factor per unit add 40% to cost
4) Inspection per unit add 15% to cost
5) Labor lost due to scrap per unit add 10% to cost

6) Rework and repair/unit add 10% to cost

7) Indirect manufacturing expense add 173% to cost

Tooling

1) Tooling materials cost

2) Tool design cost

3) Tool purchase cost

4) Tool inspection cost

These represent production costs as exist in January, 1974, at a typical production facility using the General Electric Composite Product Facility at Albuquerque, New Mexico, as the model. The line items were discussed in more detail in the Task I report.

Estimated time to manufacture the component or assembly considered the various steps necessary in processing the material and/or adhesively bonding the components together into an assembly, plus final machining.

The first article cost identified for each component of the assembly consisted of tooling, material, labor and contingencies. The average cost for 600 units was established by adding only the estimated cost for raw material and total labor cost for the first unit. A factor for waste/spoilage and cost to purchase was added to the estimated cost for raw material. The labor cost arrived at in the development phase was placed on an 86% learning curve and projected to the average cost for the 600 units. Then several factors were added to this cost to compensate for the following: 1) overrun, 2) inspection, 3) scrap, 4) rework/repair, and 5) indirect manufacturing expenses. This value was added to the total material cost to yield an average cost for the 600 units. The cost for production tooling was not factored into the 600 units as such tooling is usually amortized over a much shorter span of production.

The method and detail involved in obtaining the costs of the components investigated is illustrated in Table XIV which is a complete parts breakdown of the 1979 composite nacelle shown in Figure 42. This breakdown shows both the tooling and assembly costs for the first unit. This same type breakdown was made for all components. In some cases, such as the nacelle just shown, subcomponents such as the forward outer duct sound suppression system are shown separately as well as being included in the overall nacelle.

Table XIV. 1979 Composite Nacelle.

Date: 12/17/73

TITLE: 1979 NACELLE - COMPOSITE LAMINATE

DRAWING NUMBER: 4013096-512 (Figure 42)

STUDY:

ITEM	COMPONENT NAME	K-TOOL	UNITS/ASS'Y	HRS/UNIT	TOTAL HRS
1	Cap - De-Ice (titanium)	5	1	40	40
2	Cap - Inner	5	1	40	40
3	Flange - Transition	5	1	16	16
4	Flange	6	6 @ 60°	8	48
5	Flange - Transition	6	6 @ 60°	8	48
6	Flange	6	6 @ 60°	8	48
7	Ring (per Section B-B Typ.)	8	1	40	40
8	Flange	6	6 @ 60°	8	48
9	Flange - C.P.	8	6 @ 60°	8	48
10	Skin - A	6	1	24	24
11	Skin	6	1	16	16
12	H - C	3	1	16	16
13	Skin	6	1	16	16
14	Flange - C.P.	8	6 @ 60°	8	48
15	Flange - FM	8	6 @ 60°	8	48
16	Flange	8	6 @ 60°	8	48
17	Ring - (BB)	8	1	40	40
18	Flange	8	6/60	8	48
19	Skin - A	6	1	24	24
20	Insert - Nut		72	1/4	18
21	Skin	3	1	8	8
22	H - C	3	1	16	16
23	Skin - A	6	1	24	24
24	Bolt		72	.03	2
25	Skin	6	1	16	16
26	Skin	3	1	8	8
27	Flange	8	6/60	8	48
28	Flange - FM	8	6/60	8	48
29	Flange	8	6/60	8	48
30	Ring (B-B)	8	1	40	40
31	Flange - FM	8	6/60	8	48

Table XIV. 1979 Composite Nacelle (Continued).

Date: 12/17/73

TITLE: 1979 NACELLE - COMPOSITE LAMINATE

DRAWING NUMBER: 4013096-512 (Figure 42)

STUDY:

ITEM	COMPONENT NAME	K-TOOL	UNITS/ASS'Y	HRS/UNIT	TOTAL HRS
	(Continued)				
32	Flange	0	6/60	8	48
33	Flange	0	6/60	8	48
34	Skin	4	1	24	24
35	Skin	4	1	24	24
36	H - Comb	3	6 @ 60°	4	24
37	Skin - A	4	1	30	30
38	Flange	0	6 @ 60°	8	48
39	Flange	8	6 @ 60°	8	48
40	Ring	8	1	40	40
41	Flange	0	6 @ 60°	8	48
42	Flange	0	6 @ 60°	8	48
43	Flange	0	6/60	8	48
44	Skin - A	0	1	8	8
45	H - Comb	2	6/60	4	24
46	Mult. Flange	8	6/60	8	48
47	Skin	0	1	8	8
48	Ring Flange	8	6/60	8	48
49	Flange Ring	10	6/60	8	48
50	Flange	0	6/60	8	48
51	Void --	--	--	--	--
52	Seal	2	6/60	6	36
53	Flange	0	6/60	8	48
54	H - Comb	0	1	8	8
55	Flange	0	6/60	8	48
56	Flange	4	6/60	4	24
57	Flange - Ring	10	6/60	8	48
58	Flange	5	6/60	4	24
59	Skin	3	1	16	16
60	Flange	3	6/60	8	48
61	Ring	6	1	40	40

Table XIV. 1979 Composite Nacelle (Continued).

Date: 12/17/73

TITLE: 1979 NACELLE - COMPOSITE LAMINATE

DRAWING NUMBER: 4013096-512 (Figure 42)

STUDY:

ITEM	COMPONENT NAME	K-TOOL	UNITS/ASS'Y	HRS/UNIT	TOTAL HRS
	(Continued)				
62	Flange	0	6/60	8	48
63	Flange - Ring	0	6/60	8	48
64	Flange	0	6/60	4	24
65	Flange	0	6/60	8	48
66	Skin - A	6	1	24	24
67	Flange - Ring	10	6/60	8	48
68	Flange	8	6/60	8	48
69	Skin	6	1	16	16
70	H - Comb	3	1	16	16
71	Flange	6	6/60	8	48
72	Flange	6	6/60	8	48
73	Ring	10	1	40	40
74	Flange	6	6/60	8	48
75	Flange	8	6/60	8	48
76	Flange	8	6/60	8	48
77	Flange	6	6/60	8	48
78	Skin	3	1	16	16
79	Skin	5	1	32	32
80	H - Comb	4	6/60	4	24
81	Skin - A	4	1	20	20
82	Flange	6	6/60	6	36
83	Flange	0	6/60	6	36
84	Flange	0	6/60	8	48
85	Ring	10	1	40	40
86	Flange	10	6/60	8	48
87	Skin	3	1	8	8
88	Close Out	6	6/60	6	36
89	Cap Flange	6	6/60	6	36
90	Skin - A	4	1	20	20
91	Skin	0	1	8	8

Table XIV. 1979 Composite Nacelle (Concluded).

Date: 12/17/73

TITLE: 1979 NACELLE - COMPOSITE LAMINATE

DRAWING NUMBER: 4013096-512 (Figure 42)

STUDY:

ITEM	COMPONENT NAME	K-TOOL	UNITS/ASS'Y	HRS/UNIT	TOTAL HRS
	(Continued)				
92	Flange	5	6/60	8	48
93	Skin	0	1	8	8
94	Flange	0	6/60	6	36
95	Ring	5	1	32	32
96	Flange	0	6/60	6	36
97	Ring	5	6/60	4	24
98	Skin "U"	6	6/60	8	48
99	Flange (Filmold)	15	6/60	8	48
100	Void --	--	--	--	--
101	Void --	--	--	--	--
102	Flange	5	6/60	6	36
103	H - Comb	1	6/60	4	24
104	Skin	2	1	8	8
105	Close Out Flange	6	6/60	8	48
106	Flange	8	6/60	8	48
107	Skin - A	0	1	8	8
108	Containment Felt	1	1	8	8
109	H - Comb	3	6/60	4	24
		481K			3,618 Hrs.
110	Ass'y Tool	59K			1,382
	Total	550K			5,000 Hrs.
	3,000 Lbs. Mat'l @ $30/Lb.	90K			

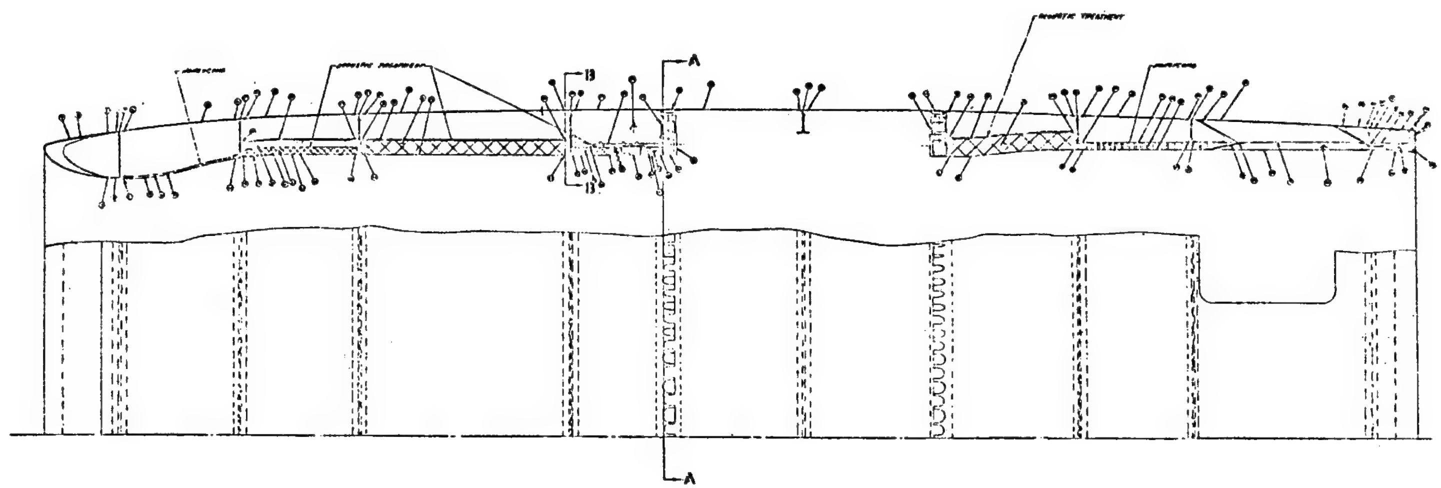


Figure 42. 1979 Composite Nacelle Parts Breakdown Diagram.

In other cases some items are combined in the summary that are shown separately in the primary cost breakdown. An example of this is the acoustical treatment on the outer by-pass duct which is shown as part of the duct assembly but was added to the nacelle for the final summary. In other cases, where portions of a composite structure were the same for different engine configurations and time periods, there is only one cost breakdown shown although it will appear in whole or in part in different summaries. Cost breakdowns are shown only for major items. Minor items, such as booster blades, appear only in the summary tables.

Cost breakdowns for the following components are presented for the 1979 engines in Tables XV through XXIV. The numbers for Materials and Labor are running totals, tooling is not included. The blade costs shown do not include the disc although this was added for the DOC and ROI studies.

- Nacelle
- Fwd Outer Duct Acoustic
- Spinner
- Aft Outer Duct and Inner Duct
- Structural Stator Case, Booster & Splitter plus Splitter only
- Structural Stator Case and Outer By-Pass
- Fan Frame Replacement
- Fan Frame Composite Design
- Fan Blades

Typical breakdowns of the various types of production costs as compared, on a percentage basis, to the metal baseline costs are shown in Table XXV for the fan frame and Table XXVI for the fan blades. Summary comparison for all components are shown in Section 3.5.5.

Those items which were different in the 1985 composite engine configuration were the following:

- Nacelle - Fixed or No Splitter
- Fwd Outer Duct Acoustic
- Inlet Splitter
- Aft Duct and Splitter
- Vane Frame
- Fan Blades

Table XV. 1979 Nacelle - Composite Laminated.

COST ESTIMATING PARAMETERS PRODUCTION (Based on 600 Sets)

Engine: 1979

Component Name: NACELLE - COMPOSITE LAMINATED (1979)

Component Description: 4013096-512

	Estimate	
Materials	**Man Hrs.**	**Direct Cost**
1. Material cost per unit		45K
2. Waste & spoilage cost per unit 110%		49,500
3. Unreported losses per unit 112%		55,440
4. Expense of material procurement/unit 107%		59,320
Labor		
1. Production set-up/check-out cost/unit	50	
2. Manufacture of part	1,250	
3. Overrun factor per unit 140%	1,820	
4. In-process and final inspection per unit 115%	2,093	
5. Labor lost due to scrap per unit 110%	2,302	
6. In-process rework and repair per unit 110%	2,533	
7. Indirect manufacturing expense per unit 173%	4,381	
Labor Subtotal of Items Nos. 6 & 7	6,914	
Tooling		
1. Tooling materials	200	20K
2. Design of all tools and fixtures	5,000	
3. Procurement of all tools and fixtures	1,500	550K
4. In-process and final inspection of tools	2,000	

Table XVI. Forward Outer Duct Sound Suppression System (1979).

COST ESTIMATING PARAMETERS PRODUCTION (Based on 600 Sets)

Engine: 1979

Component Name: FWD OUTER DUCT SOUND SUPPRESSION SYSTEM

Component Description: Sound suppression sandwich construction consisting of double diamond Kevlar/epoxy core bonded to Kevlar/epoxy skins & metal attachments.

	Estimate: Man Hrs.	Estimate: Direct Cost
Materials		
1. **Material cost per** assem. @ $25/Lb. Kevlar/E & metal hardware		7,000.
2. **Waste & spoilage cost per** assem. @ 110%		7,700.
3. **Unreported losses per** assem. @ 112%		8,624.
4. **Expense of material procurement/**assem. @ 107%		9,227.
Labor		
1. **Production set-up/check-out cost/** assem.	24	
2. **Manufacture of** assem.	470	
3. **Overrun factor per** assem. +140%	658	
4. **In-process and final inspection per** assem. +115%	755	
5. **Labor lost due to scrap per** assem. +110%	830	
6. **In-process rework and repair per** assem. +110%	913	
7. **Indirect manufacturing expense per** assem. +173%	1,580	
Labor Subtotal of Items Nos. 6 & 7	2,493	
Tooling		
1. **Tooling materials**	100	25,000.
2. **Design of all tools and fixtures**	2,500	
3. **Procurement of all tools and fixtures**	500	112,000.
4. **In-process and final inspection of tools**	600	

Table XVII. Spinner Sound Suppression (1979).

COST ESTIMATING PARAMETERS PRODUCTION (Based on 600 Sets)

Engine: 1979

Component Name: SPINNER SOUND SUPPRESSION

Component Description: Sound suppression sandwich construction using double diamond core & Kevlar/epoxy facings (outer face perforated - inner face non perforated)

	Estimate	
Materials	**Man Hrs.**	**Direct Cost**
1. **Material cost per unit** @ $10/Lb. (42 Lbs) plus Metal Hardware		500.
2. **Waste & spoilage cost per unit** @ 110%		550.
3. **Unreported losses per unit** @ 112%		616.
4. **Expense of material procurement/unit** @ 107%		659.
Labor		
1. **Production set-up/check-out cost/unit**	8	
2. **Manufacture of part**	60	
3. **Overrun factor per unit** +140%	84	
4. **In-process and final inspection per unit** +115%	96	
5. **Labor lost due to scrap per unit** +110%	106	
6. **In-process rework and repair per unit** +110%	117	
7. **Indirect manufacturing expense per unit** +173%	200	
Labor Subtotal of Item Nos. 6 & 7	317	
Tooling		
1. **Tooling materials**	8	200.
2. **Design of all tools and fixtures**	360	
3. **Procurement of all tools and fixtures**	100	14,000.
4. **In-process and final inspection of tools**	40	

Table XVIII. Duct, Inner and Outer, No Splitter (1979).

COST ESTIMATING PARAMETERS — PRODUCTION (Based on 600 Sets)

Engine: 1979

Component Name: DUCT - INNER & OUTER (NO SPLITTER)

Component Description: 4013096-502

	Estimate	
Materials	**Man Hrs.**	**Direct Cost**
1. **Material cost per unit** (789 Lb. x $32/Lb)		25,248
2. **Waste & spoilage cost per unit** 110%		27,772
3. **Unreported losses per unit** 112%		31,105
4. **Expense of material procurement/unit** 107%		33,282
Labor		
1. **Production set-up/check-out cost/unit**	15	
2. **Manufacture of part**	360	
3. **Overrun factor per unit** 140%	525	
4. **In-process and final inspection per unit** 115%	603	
5. **Labor lost due to scrap per unit** 110%	664	
6. **In-process rework and repair per unit** 110%	730	
7. **Indirect manufacturing expense per unit** 173%	1,272	
Labor Subtotal for Item Nos. 6 & 7	2,002	
Tooling		
1. **Tooling materials**		10K
2. **Design of all tools and fixtures**	4,000	
3. **Procurement of all tools and fixtures**		200K
4. **In-process and final inspection of tools**	2,000	

Table XIX. Stator Case Booster and Splitter (1979).

COST ESTIMATING PARAMETERS PRODUCTION (Based on 600 Sets)

Engine: 1979

Component Name: STATOR CASE BOOSTER & SPLITTER (1979)

Component Description: 4013096-498

	Estimate	
Materials 50% Each - GR/Epoxy @ $30/Lb. & GR/PI @ $35/Lb.	**Man Hrs.**	**Direct Cost**
1. Material cost per unit ~ $32.50 x 396 Lbs.		12,870
2. Waste & spoilage cost per unit 110%		14,157
3. Unreported losses per unit 112%		15,856
4. Expense of material procurement/unit 107%		16,965
Labor		
1. Production set-up/check-out cost/unit	25	
2. Manufacture of part	2,300	
3. Overrun factor per unit 140%	3,255	
4. In-process and final inspection per unit 115%	3,743	
5. Labor lost due to scrap per unit 110%	4,117	
6. In-process rework and repair per unit 110%	4,529	
7. Indirect manufacturing expense per unit 173%	7,836	
Labor Subtotal of Item Nos. 6 & 7	12,365	
Tooling		
1. Tooling materials		10K
2. Design of all tools and fixtures	3,000	
3. Procurement of all tools and fixtures		500K
4. In-process and final inspection of tools	500	

Table XX. 1979 Splitter Only.

COST ESTIMATING PARAMETERS PRODUCTION (Based on 600 Sets)

Engine: 1979

Component Name: SPLITTER ONLY

Component Description: 4013096-498 LESS -495

	Estimate	
Materials	Man Hrs.	Direct Cost
1. Material cost per unit $32.50 x 176 Lbs.		5,720
2. Waste & spoilage cost per unit 110%		6,292
3. Unreported losses per unit 112%		7,047
4. Expense of material procurement/unit 107%		7,540
Labor		
1. Production set-up/check-out cost/unit	15	
2. Manufacture of part	1,600	
3. Overrun factor per unit 140%	2,261	
4. In-process and final inspection per unit 115%	2,600	
5. Labor lost due to scrap per unit 110%	2,860	
6. In-process rework and repair per unit 110%	3,146	
7. Indirect manufacturing expense per unit 173%	5,443	
Labor Subtotal of Item Nos. 6 & 7	8,589	
Tooling		
1. Tooling materials		5K
2. Design of all tools and fixtures	2,000	
3. Procurement of all tools and fixtures		300K
4. In-process and final inspection of tools	300	

Table XXI. 1979 Structural Stator Case, Outer Bypass.

COST ESTIMATING PARAMETERS PRODUCTION (Based on 600 Sets)

Engine: 1979

Component Name: STRUCTURAL STATOR CASE, OUTER BY-PASS (1979)

Component Description: 4013096-495

	Estimate	
Materials GR/Epoxy @ $30/Lb.	**Man Hrs.**	**Direct Cost**
1. Material cost per unit 220# x $30/Lb.		6,600
2. Waste & spoilage cost per unit 110%		7,260
3. Unreported losses per unit 112%		8,131
4. Expense of material procurement/unit 107%		8,700
Labor		
1. Production set-up/check-out cost/unit	20	
2. Manufacture of part	750	
3. Overrun factor per unit 140%	1,078	
4. In-process and final inspection per unit 115%	1,240	
5. Labor lost due to scrap per unit 110%	1,364	
6. In-process rework and repair per unit 110%	1,500	
7. Indirect manufacturing expense per unit 173%	2,596	
Labor Subtotal for Item Nos. 6 & 7	4,096	
Tooling		
1. Tooling materials		10K
2. Design of all tools and fixtures	2,000	
3. Procurement of all tools and fixtures		250K
4. In-process and final inspection of tools	250	

Table XXII. 1979 Fan Frame, Composite Replacement.

COST ESTIMATING PARAMETERS PRODUCTION (Based on 600 Sets)

Engine: 1979

Component Name: FAN FRAME - COMPOSITE 1979 REPLACEMENT

Component Description: 4013096-480

	Estimate Man Hrs.	Estimate Direct Cost
Materials Graphite/Epoxy @ $30 & GR/PI @ $35		
1. Material cost per unit (Avg. = $32/Lb) (50-50%)		12,500
2. Waste & spoilage cost per unit 110%		13,800
3. Unreported losses per unit 112%		16,500
4. Expense of material procurement/unit 107%		17,600
Labor		
1. Production set-up/check-out cost/unit	20	
2. Manufacture of part	1,000	
3. Overrun factor per unit 140%	1,400	
4. In-process and final inspection per unit 115%	1,610	
5. Labor lost due to scrap per unit 110%	1,771	
6. In-process rework and repair per unit 110%	1,948	
7. Indirect manufacturing expense per unit 173%	3,370	
Labor Subtotal of Item Nos. 6 & 7	5,318	
Tooling		
1. Tooling materials	100	10K
2. Design of all tools and fixtures	4,000	
3. Procurement of all tools and fixtures	1,000	300K
4. In-process and final inspection of tools	2,000	

Table XXIII. 1979 Fan Frame, Composite.

COST ESTIMATING PARAMETERS — PRODUCTION (Based on 600 Sets)

Engine: 1979

Component Name: FAN FRAME - COMPOSITE (1979)

Component Description: 4013096-487

	Estimate	
Materials 50% Graphite/Epoxy; 50% GR/PI	Man Hrs.	Direct Cost
1. Material cost per unit $32/Lb Avg.		11.2K
2. Waste & spoilage cost per unit 110%		12.4K
3. Unreported losses per unit 112%		13.9K
4. Expense of material procurement/unit 107%		14.9K
Labor		
1. Production set-up/check-out cost/unit	10	
2. Manufacture of part	750	
3. Overrun factor per unit 140%	1,050	
4. In-process and final inspection per unit 105%	1,100	
5. Labor lost due to scrap per unit 110%	1,215	
6. In-process rework and repair per unit 110%	1,340	
7. Indirect manufacturing expense per unit 173%	2,270	
Labor Subtotal for Item Nos. 6 & 7	3,610	
Tooling		
1. Tooling materials		10K
2. Design of all tools and fixtures	3,000	
3. Procurement of all tools and fixtures		450K
4. In-process and final inspection of tools	200	

Table XXIV. 1979 Stage 1 Fan Blade Set.

COST ESTIMATING PARAMETERS PRODUCTION (Based on 600 Sets)

Engine: 1979

Component Name: Stage 1 Fan Blade Set

Component Description: Hybrid Composite Blades 22 blades per set

	Estimate Man Hrs.	Estimate Direct Cost
Materials		
1. **Material cost per unit** set @ $30/lb 7.08 lb/blade		4673
2. **Waste & spoilage cost per unit** 130%		6075
3. **Unreported losses per unit** 110%		6682
4. **Expense of material procurement/unit** 107%		7150
Labor		
1. **Production set-up/check-out cost/unit** set	4	
2. **Manufacture of part** 10 hrs/Blade	220	
3. **Overrun factor per unit** 140%	308	
4. **In-process and final inspection per unit** 115%	354	
5. **Labor lost due to scrap per unit** 110%	309	
6. **In-process rework and repair per unit** 110%	420	
7. **Indirect manufacturing expense per unit** 173% (Albuquerque)	741	
Labor Subtotal For Item Nos. 6 & 7	1,161	
Tooling		
1. **Tooling materials**	100	20,000
2. **Design of all tools and fixtures**	1000	
3. **Procurement of all tools and fixtures**	400	250,000
4. **In-process and final inspection of tools**	1000	50,000

Table XXV. 1979 Fan Frame Production Parameters.

Engine: 1979		
Component Name: FAN FRAME 4013096-480 & 487		
Component Description: SEE DRAWINGS		
Baseline @ 100% - CF6-6 FAN FRAME - 9021M11 - (1973) - WEIGHS 750 LBS.		
Composite Design - FAN FRAME/OUTER CASE - (1979) - 4013096-487 - 353 LBS.		
Material Replacement - FAN FRAME - COMPOSITE (1979) 4013096-480 - 390 LBS.		
Rationale for Comparison: Fan Frame structure serves same function in all three cases.		
PRODUCTION PARAMETERS	**Comparison to 100% Baseline**	
	Composite Design	**Mat'l Replacement**
1. Bulk Material Cost/Lb. (%)	600	600
2. Unit Weight (%)	47	52
3. Rate Tooling Cost (%)	50	42
4. Quality Control Cost/Unit (%)	100	100
5. Maintenance Cost (%)	100	100
6. Field Inspection Cost (%)	100	100
7. Life Expectance (Time)(%)	100	100
8. Unit Cost (%)	75	98

Table XXVI. 1979 Stage 1 Fan Blade Set.

Engine: 1979		
Component Name: Stage 1 Fan Blade Set		
Component Description: Hybrid composite blades 22 blades per set		
Baseline @ 100% - A 46 blade set of titanium 6-4 tip shrouded blades		
Composite Design - A 22 blade set of hybrid composite blades		
Material Replacement - N/A		
Rationale for Comparison: CF6 titanium fan blades and TF39 Stage 1 hybrid composite blade.		
	Comparison to 100% Baseline	
PRODUCTION PARAMETERS	**Composite Design**	**Mat'l Replacement**
1. Bulk Material Cost/Lb.	75%	
2. Unit Weight	67%	
3. Rate Tooling Cost	60%	
4. Quality Control Cost/Unit	100%	
5. Maintenance Cost	105%	
6. Field Inspection Cost	105%	
7. Life Expectance (Time) %	100%	
8. Unit Cost	36%	

Cost and labor breakdowns for these components are shown in Tables XXVII through XXXII. Again, component summaries are shown in Section 3.5.5

3.5.3 Development Costs

The major differences in the development cost for a composite component over a metal component lie in the amount of material and process development effort involved due to the use of a new material system that is radically different, from a materials and process standpoint, from the types of materials currently used in today's jet engines. The costs shown in this section deal mainly with this extra development cost although normal design development costs are shown which are used to obtain a development complexity factor.

In arriving at the costs for Development (materials research and process development) a detailed list of work was considered and a value placed upon each segment of the effort. The detail of this effort is identified below.

Materials Research & Process Development

- Material selection
  - Literature search
  - Industry survey
  - Analysis of literature search & industry survey
- Identification of material supplier
- Rough draft Specification
- Approve Specification final draft
- Certify material supplier to Specifications
- Obtain material selected
- Plan testing program to confirm mechanical and physical properties
- Fabricate test panels and specimens from several lots of material
- Conduct test program on specimens
- Analyze test data
- Establish standard deviation limits
- Document data for design handbook

Table XXVII. 1985 Nacelle, Composite.

COST ESTIMATING PARAMETERS PRODUCTION (Based on 600 Sets)

Engine: 1985

Component Name: NACELLE - COMPOSITE

Component Description: FIXED INLET WITH SPLITTER 4013179-250 OR VARIABLE INLET WITHOUT SPLITTER

	Estimate	
Materials	**Man Hrs.**	**Direct Cost**
1. Material cost per unit 2000# x $10/1b		20,000
2. Waste & spoilage cost per unit 110%		22,000
3. Unreported losses per unit 112%		24,640
4. Expense of material procurement/unit 107%		26,364
Labor		
1. Production set-up/check-out cost/unit	50	
2. Manufacture of part	2,000	
3. Overrun factor per unit 140%	2,870	
4. In-process and final inspection per unit 115%	3,300	
5. Labor lost due to scrap per unit 110%	3,630	
6. In-process rework and repair per unit 110%	3,993	
7. Indirect manufacturing expense per unit 173%	6,908	
Labor Subtotal for Item Nos. 6 & 7	10,901	
Tooling		
1. Tooling materials		30K
2. Design of all tools and fixtures	6,000	
3. Procurement of all tools and fixtures		900K
4. In-process and final inspection of tools	3,000	

Table XXVIII. 1985 Forward Outer Ducting.

COST ESTIMATING PARAMETERS PRODUCTION (Based on 600 Sets)

Engine: 1985

Component Name: FORWARD OUTER DUCTING

Component Description: 4013176-824

	Estimate	
Materials	**Man Hrs.**	**Direct Cost**
1. Material cost per assem. 200 Lbs. @ $10/Lb GR/E & metal Hardware		3,500.
2. Waste & spoilage cost per assem. @ 110%		3,850.
3. Unreported losses per assem. @ 112%		4,301.
4. Expense of material procurement/ assem. @ 107%		4,331.
Labor		
1. Production set-up/check-out cost/ assem.	32	
2. Manufacture of assem.	610	
3. Overrun factor per assem. +140%	900	
4. In-process and final inspection per assem. +115%	1,035	
5. Labor lost due to scrap per assem. +110%	1,138	
6. In-process rework and repair per assem. +110%	1,252	
7. Indirect manufacturing expense per assem. +173%	2,160	
Labor Subtotal for Item Nos. 6 & 7	3,412	
Tooling		
1. Tooling materials	500	25,000.
2. Design of all tools and fixtures	2,500	
3. Procurement of all tools and fixtures	500	120,000.
4. In-process and final inspection of tools	600	

Table XXIX. 1985 Forward Splitter.

COST ESTIMATING PARAMETERS PRODUCTION (Based on 600 Sets)

Engine: 1985

Component Name: FWD SPLITTER

Component Description: Sound suppression sandwich construction using double diamond core bonded to perforated faces of GR/epoxy & metal inserts & other hardware

	Estimate	
Materials	**Man Hrs.**	**Direct Cost**
1. **Material cost per** assem. 170 Lbs. @ $10/Lb + metal hardware		2,500.
2. **Waste & spoilage cost per** assem. @ 110%		2,750.
3. **Unreported losses per** assem. @ 112%		3,089.
4. **Expense of material procurement/**assem. @ 107%		3,111.
Labor		
1. **Production set-up/check-out cost/** assem.	32	
2. **Manufacture of** assem.	382	
3. **Overrun factor per** assem. +140%	535	
4. **In-process and final inspection per** assem. +115%	615	
5. **Labor lost due to scrap per** assem. +110%	676	
6. **In-process rework and repair per** assem. +110%	743	
7. **Indirect manufacturing expense per** assem. +173%	1,285	
Labor Subtotal for Item Nos. 6 & 7	2,028	
Tooling		
1. **Tooling materials**	500	20,000.
2. **Design of all tools and fixtures**	3,000	
3. **Procurement of all tools and fixtures**	800	160,000.
4. **In-process and final inspection of tools**	1,000	

Table XXX. 1985 Aft Duct.

COST ESTIMATING PARAMETERS PRODUCTION (Based on 600 Sets)

Engine: 1985

Component Name: AFT DUCT - INNER & OUTER & SPLITTER

Component Description: 4013096-502

	Estimate	
Materials	**Man Hrs.**	**Direct Cost**
1. **Material cost per unit** (952 Lb. x $11/Lb)		10,472
2. **Waste & spoilage cost per unit** 110%		11,519
3. **Unreported losses per unit** 112%		12,901
4. **Expense of material procurement/unit** 107%		13,804
Labor		
1. **Production set-up/check-out cost/unit**	20	
2. **Manufacture of part**	520	
3. **Overrun factor per unit** 140%	756	
4. **In-process and final inspection per unit** 115%	869	
5. **Labor lost due to scrap per unit** 110%	956	
6. **In-process rework and repair per unit** 110%	1,052	
7. **Indirect manufacturing expense per unit** 173%	1,819	
Labor Subtotal for Item Nos. 6 & 7	2,871	
Tooling		
1. **Tooling materials**		10
2. **Design of all tools and fixtures**	5,000	
3. **Procurement of all tools and fixtures**		275
4. **In-process and final inspection of tools**	2,500	

Table XXXI. 1985 Vane Frame, Composite.

COST ESTIMATING PARAMETERS PRODUCTION (Based on 600 Sets)

Engine: 1985

Component Name: VANE FRAME - COMPOSITE (1985)

Component Description: 4013096-492 (NO SPLITTER)

	Estimate Man Hrs.	Estimate Direct Cost
Materials 50% Each - GR/Epoxy @ $10/Lb. & GR/PI @ $12/Lb.		
1. **Material cost per unit** @ $11/Lb. x 300 Lbs.		3,100
2. **Waste & spoilage cost per unit** 110%		3,410
3. **Unreported losses per unit** 112%		3,819
4. **Expense of material procurement/unit** 107%		4,086
Labor		
1. **Production set-up/check-out cost/unit**	10	
2. **Manufacture of part**	750	
3. **Overrun factor per unit** 140%	1,050	
4. **In-process and final inspection per unit** 115%	1,100	
5. **Labor lost due to scrap per unit** 110%	1,215	
6. **In-process rework and repair per unit** 110%	1,340	
7. **Indirect manufacturing expense per unit** 173%	2,270	
Labor Subtotal for Item Nos. 6 & 7	3,610	
Tooling *		
1. **Tooling materials**		10K
2. **Design of all tools and fixtures**	3,500	
3. **Procurement of all tools and fixtures**		400K
4. **In-process and final inspection of tools**	600	

* TOTAL TOOL COST EQUALS $467K + SPLITTER $333K = $700K
SPLITTER TOOLING DEFINED ON 1979 SPLITTER 4013096-498 COST BREAKDOWN

Table XXXII. 1985 Stage 1 Fan Blade Set.

COST ESTIMATING PARAMETERS PRODUCTION (Based on 600 Sets)

Engine: 1985

Component Name: Stage 1 Fan Blade Set

Component Description: Hybrid composite blades 26 blades per set

Materials	**Estimate: Man Hrs.**	**Estimate: Direct Cost**
1. **Material cost per unit** set @ $10/lb		1557
2. **Waste & spoilage cost per unit** 130%		2024
3. **Unreported losses per unit** 110%		2226
4. **Expense of material procurement/unit** 107%		2382
Labor		
1. **Production set-up/check-out cost/unit**	4	
2. **Manufacture of part**	198	
3. **Overrun factor per unit** 140%	277	
4. **In-process and final inspection per unit** 115%	319	
5. **Labor lost due to scrap per unit** 110%	350	
6. **In-process rework and repair per unit** 110%	386	
7. **Indirect manufacturing expense per unit** 173% (Albuquerque)	667	
Labor Subtotal for Item Nos. 6 & 7	1,053	
Tooling		
1. **Tooling materials**	100	20,000
2. **Design of all tools and fixtures**	1000	
3. **Procurement of all tools and fixtures**	400	250,000
4. **In-process and final inspection of tools**	1000	50,000

Materials & Process Refinement

- Define plan for subscale configuration process studies
- Design & obtain subscale tooling for process studies
- Obtain materials for fabrication of subscale shapes and establish process limits
- Write plan to fabricate subscale components to refine process
- Fabricate subscale components to demonstrate refined process
- Evaluate subscale component on basis of processing
- Document process parameters

Design & Manufacturing Considerations

- Define design limitations for the material & process established
- Provide design guidance to design engineering for structural, environmental and economic considerations
- Coordinate design changes with design engineering during subscale fabrication and demonstration
- Establish cost & weight limits
- Subscale component NDE & DE

Design & Procure Development Tooling

- Establish tooling concept
- Coordinate tool concepts with Production Engineering
- Design tools
- Review tool designs & approve
- Write request to purchase tools
- Approve tooling source
- Fund tooling
- Liaison tooling
- Approve completion of tooling
- Receive tool & tool proof for dimensional checks
- Accept tool

Process Development & Refinement

- Define plan to refine process on full-scale component
- Run heat-up rates on tooling

- Manufacture full-scale hardware
- Cut up components to confirm process material properties
- Document process and transition to production
- Confirm that process will be successful in production environment

<u>Perform Nondestructive Evaluation (NDE) & Destructive Evaluation (DE) Analysis</u>

- Select NDE method suitable to the configuration and construction
- Obtain instruments or modify existing equipment to conduct the selected NDE method
- Conduct trial NDE first on subscale component
- Confirm NDE method by cutting up (DE) subscale component
- Document NDE indications and limits
- Conduct NDE on full-scale component
- Conduct NDE indications by DE (1) full-scale component
- Document NDE technique and transition to production
- Confirm use of the NDE method in production environment

<u>Transmit Development to Production</u>

- Write & issue the recommended process procedures to be used in converting materials to hardware
- Write & issue document to transition NDE and DE methods to be used in production
- Demonstrate feasibility of process, NDE & DE at the production facility

The total number of hours and direct cost as shown in Tables XXXIII through XLII for each component development is based upon January, 1974, parameters. Sensitivity factors for such unknowns as the effects of labor demands, energy crisis as it relates to transportation, material shortages, lead time effect on materials, tooling and supporting metal hardware, strategic material priorities, and others have not been factored in the cost estimates. Labor rates used for development are typically laboratory scale and are higher than labor rates used for production.

Table XXXIII. 1979 Nacelle, Composite Laminate, Development.

COST ESTIMATING PARAMETERS

Engine: 1979

Component Name: NACELLE - COMPOSITE LAMINATE (1979)

Component Description: 4013096-512

Effort Description	Estimate	
	Man Hrs.	Direct Cost
1. Materials Research	4,000	
2. Materials & Process Refinement	4,000	60K
3. Mechanical & Physical Definition of Component		
4. Design/Manufacturing Considerations	3,000	40K
5. Design & Procure Development Tooling	4,000	550K
6. Process Development & Refinement	5,000	100K
7. Perform NDE and DE Analysis	2,000	20K
8. Transmit Development to Production	4,000	60K

Table XXXIV. 1979 Forward Outer Duct Sound Suppression System, Development.

COST ESTIMATING PARAMETERS

Engine: 1979

Component Name: FWD OUTER DUCT SOUND SUPPRESSION SYSTEM

Component Description: Sound suppression sandwich construction using double diamond core bonded to perforated face sheets & solid back laminates of Kevlar/Epoxy material & metal inserts for attach.

Effort Description	Estimate	
	Man Hrs.	Direct Cost
1. Materials Research	1,000	5,000.
2. Materials & Process Refinement	3,000	60,000.
3. Mechanical & Physical Definition of Component		
4. Design/Manufacturing Considerations	1,000	10,000.
5. Design & Procure Development Tooling	3,000	50,000.
6. Process Development & Refinement	2,000	10,000.
7. Perform NDE and DE Analysis	1,000	
8. Transmit Development to Production	2,000	

Table XXXV. 1979 Spinner Sound Suppression, Development.

COST ESTIMATING PARAMETERS

Engine: 1979

Component Name: SPINNER SOUND SUPPRESSION

Component Description: Sound suppression sandwich construction using double diamond core & Kevlar/epoxy facings (outer face perforated)

Effort Description	Estimate	
	Man Hrs.	Direct Cost
1. Materials Research	1,000	5,000.
2. Materials & Process Refinement	3,000	60,000.
3. Mechanical & Physical Definition of Component		
4. Design/Manufacturing Considerations	1,000	8,000.
5. Design & Procure Development Tooling	1,000	6,000.
6. Process Development & Refinement	280	5,000.
7. Perform NDE and DE Analysis	500	
8. Transmit Development to Production	1,000	

Table XXXVI. 1979 Duct, Inner and Outer (No Splitter), Development.

COST ESTIMATING PARAMETERS

Engine: 1979

Component Name: DUCT - INNER & OUTER (NO SPLITTER) - 1979

Component Description: 4013096-502

Effort Description	Estimate	
	Man Hrs.	Direct Cost
1. Materials Research	3,000	
2. Materials & Process Refinement	3,000	40K
3. Mechanical & Physical Definition of Component		
4. Design/Manufacturing Considerations	2,000	20K
5. Design & Procure Development Tooling	1,800	175K
6. Process Development & Refinement	1,440	55K
7. Perform NDE and DE Analysis	1,500	10K
8. Transmit Development to Production	4,000	40K

Table XXXVII. 1979 Stator Case Booster and Splitter, Development.

COST ESTIMATING PARAMETERS

Engine: 1979

Component Name: STATOR CASE BOOSTER & SPLITTER (1979)

Component Description: 4013096-498

Effort Description	Estimate Man Hrs.	Estimate Direct Cost
1. Materials Research	4,000	
2. Materials & Process Refinement	4,000	60K
3. Mechanical & Physical Definition of Component		
4. Design/Manufacturing Considerations	3,000	40K
5. Design & Procure Development Tooling	2,500	300K
6. Process Development & Refinement	9,000	60K
7. Perform NDE and DE Analysis	2,000	15K
8. Transmit Development to Production	4,000	40K

Table XXXVIII. 1979 Structural Stator Case, Outer Bypass, Development.

COST ESTIMATING PARAMETERS

Engine: 1979

Component Name: STRUCTURAL STATOR CASE, OUTER BY-PASS (1979)

Component Description: 4013096-495

Effort Description	Estimate	
	Man Hrs.	Direct Cost
1. Materials Research	4,000	
2. Materials & Process Refinement	3,000	50K
3. Mechanical & Physical Definition of Component		
4. Design/Manufacturing Considerations	2,000	30K
5. Design & Procure Development Tooling	1,500	220K
6. Process Development & Refinement	3,100	40K
7. Perform NDE and DE Analysis	1,500	10K
8. Transmit Development to Production	3,000	30K

Table XXXIX. 1979 Fan Frame, Composite, Development.

COST ESTIMATING PARAMETERS

Engine: 1979 MAT'L REPLACEMENT

Component Name: FAN FRAME - COMPOSITE 1979

Component Description: 4013096-480

Effort Description	Estimate	
	Man Hrs.	Direct Cost
1. Materials Research	4,000	
2. Materials & Process Refinement	4,000	60K
3. Mechanical & Physical Definition of Component		
4. Design/Manufacturing Considerations	3,000	40K
5. Design & Procure Development Tooling	2,000	270K
6. Process Development & Refinement	4,000	30K
7. Perform NDE and DE Analysis	2,000	15K
8. Transmit Development to Production	4,000	40K

Table XL. 1979 Fan Frame, Composite, Development.

COST ESTIMATING PARAMETERS

Engine: 1979 COMPOSITE

Component Name: FAN FRAME - COMPOSITE (1979)

Component Description: 4013096-487

Effort Description	Estimate	
	Man Hrs.	Direct Cost
1. Materials Research	4,000	
2. Materials & Process Refinement	3,000	50K
3. Mechanical & Physical Definition of Component		
4. Design/Manufacturing Considerations	2,000	30K
5. Design & Procure Development Tooling	1,000	220K
6. Process Development & Refinement	3,000	35K
7. Perform NDE and DE Analysis	1,500	10K
8. Transmit Development to Production	3,000	30K

Table XLI. 1979 Stage 1 Fan Blade Set, Development.

COST ESTIMATING PARAMETERS

Engine: 1979

Component Name: Stage 1 Fan Blade Set

Component Description: Hybrid Composite Blades

22 blades per set

Effort Description	Estimate	
	Man Hrs.	Direct Cost
1. Materials Research	1000	4000
2. Materials & Process Refinement	2000	4000
3. Mechanical & Physical Definition of Component	2000	
4. Design/Manufacturing Considerations		
5. Design & Procure Development Tooling	300	100,000
6. Process Development & Refinement	900	5000
7. Perform NDE and DE Analysis	1000	5000
8. Transmit Development to Production	2000	

Table XLII. 1985 Nacelle, Composite, Development.

COST ESTIMATING PARAMETERS

Engine: 1985

Component Name: NACELLE - COMPOSITE

Component Description: FIXED INLET WITH SPLITTER - 4013179-250 OR VARIABLE INLET WITHOUT SPLITTER

Effort Description	Estimate	
	Man Hrs.	Direct Cost
1. Materials Research	4,000	
2. Materials & Process Refinement	4,000	50K
3. Mechanical & Physical Definition of Component		
4. Design/Manufacturing Considerations	3,000	40K
5. Design & Procure Development Tooling	5,000	900K
6. Process Development & Refinement	8,000	100K
7. Perform NDE and DE Analysis	2,000	20K
8. Transmit Development to Production	6,000	60K

Table XLIII. 1985 Forward Outer Ducting, Development.

COST ESTIMATING PARAMETERS

Engine: 1985

Component Name: FWD OUTER DUCTING 4013176-824

Component Description: Sound suppression sandwich construction using double diamond core bonded to perforated face sheets & solid back laminates of graphite fiber/epoxy and metal inserts for attach.

Effort Description	Estimate	
	Man Hrs.	Direct Cost
1. Materials Research	1,000	5,000
2. Materials & Process Refinement	3,000	60,000
3. Mechanical & Physical Definition of Component		
4. Design/Manufacturing Considerations	1,000	10,000
5. Design & Procure Development Tooling	3,000	50,000
6. Process Development & Refinement	2,600	10,000
7. Perform NDE and DE Analysis	1,000	
8. Transmit Development to Production	2,000	

Table XLIV. 1985 Forward Splitter, Development.

COST ESTIMATING PARAMETERS

Engine: 1985

Component Name: FWD SPLITTER 4013176-824

Component Description:

MATERIAL GRAPHITE/EPOXY

Effort Description	Estimate	
	Man Hrs.	Direct Cost
1. Materials Research	1,000	5,000.
2. Materials & Process Refinement	3,000	60,000.
3. Mechanical & Physical Definition of Component		
4. Design/Manufacturing Considerations	1,000	10,000.
5. Design & Procure Development Tooling		
6. Process Development & Refinement	1,600	12,000.
7. Perform NDE and DE Analysis	1,000	
8. Transmit Development to Production	2,000	

Table XLV. 1985 Aft Duct, Inner and Outer and Splitter, Development.

COST ESTIMATING PARAMETERS

Engine: 1985

Component Name: AFT DUCT - INNER & OUTER & SPLITTER - 1985

Component Description: 4013096-502

Effort Description	Estimate Man Hrs.	Estimate Direct Cost
1. Materials Research	3,000	
2. Materials & Process Refinement	3,000	40K
3. Mechanical & Physical Definition of Component		
4. Design/Manufacturing Considerations	2,000	20K
5. Design & Procure Development Tooling	2,500	250K
6. Process Development & Refinement	2,100	70K
7. Perform NDE and DE Analysis	2,000	15K
8. Transmit Development to Production	5,000	50K

Table XLVI. 1985 Vane Frame, Composite, Development.

COST ESTIMATING PARAMETERS

Engine: 1985

Component Name: VANE FRAME COMPOSITE (1985)

Component Description: 4013096-492 (NO SPLITTER)

Effort Description	Estimate	
	Man Hrs.	Direct Cost
1. Materials Research	4,000	
2. Materials & Process Refinement	4,000	60K
3. Mechanical & Physical Definition of Component		
4. Design/Manufacturing Considerations	3,000	40K
5. Design & Procure Development Tooling	1,400	200K
6. Process Development & Refinement	3,100	40K
7. Perform NDE and DE Analysis	2,000	15K
8. Transmit Development to Production	4,000	40K

Table XLVII. 1985 Stage 1 Fan Blade Set, Development.

COST ESTIMATING PARAMETERS

Engine: 1985

Component Name: Stage 1 Fan Blade Set

Component Description: Hybrid composite blades 26 blades per set

Effort Description	Estimate	
	Man Hrs.	Direct Cost
1. Materials Research	200	2000
2. Materials & Process Refinement	600	2000
3. Mechanical & Physical Definition of Component	1000	
4. Design/Manufacturing Considerations		
5. Design & Procure Development Tooling	300	100,000
6. Process Development & Refinement	800	5000
7. Perform NDE and DE Analysis	1000	5000
8. Transmit Development to Production	1000	

Table XLVIII is a summary of the development costs, except for turbine blades, grouped in the final comparison categories as discussed in Section 3.3.8 and shown in Table XII. Also in Table XLVIII are shown the standard engineering development costs such as design and test cost which were assumed to be similar to costs for a metal structure. The total of these costs and the material and process costs produce the total development cost for each composite part. The development complexity factor is obtained by dividing this total cost by the standard development costs.

Table XLIX presents the estimated material development costs and blade pilot production costs for the turbine blades. The pilot production includes all blades needed for engine testing up to production release.

3.5.4 Maintenance

The life cycle costs that were considered in arriving at some realistic value for introducing advanced composites in jet engine hardware investigated what specific areas of work contributed to the total cost. The areas of work studied included the following:

1) Materials

2) Materials and process development

3) Prototype tooling

4) First article manufacture

5) Production tooling (rate)

6) Production fabrication

7) Repair and maintainability

Items 1 through 6 have been discussed in the previous sections. This information was readily available from records maintained in development and production facilities. However, the complete record of repair and maintainability includes records maintained in-house plus records maintained at the various overhaul centers established by the airlines. It was decided that a realistic accounting of the level of repair and maintenance could be obtained from the two largest overhaul centers; therefore, these locations were visited. They included the American Airlines Maintenance and Engineering Center at Tulsa, Oklahoma, and the United Airlines Maintenance and Engineering Center at San Francisco, California. Each maintenance and engineering center visited and those contacted by telephone said that no record of repair and maintenance is kept on secondary structures. All fiber reinforced composites currently used on commercial airframe and engines are considered secondary structures. When composite primary structures are introduced, a record of repair and maintenance will be kept. In general, the composites now used on airframe and engines have <u>not</u> needed repair beyond the 3,000-hour service life

Table XLVIII. Engineering and Development Cost Breakdown

Component	Replacement[1]				Redesign [1]			
	1979							
	Engrg Dev. Cost	Mat'l & Process Dev. Cost	Total Dev. Cost	Complexity Factor**	Engrg Dev. Cost	Mat'l Process Dev. Cost	Total Dev. Cost	Complexity Factor**
Nacelle	856	1,500	2,356	2.75	856	955	1,811	2.11
Spinner	135	219	354	2.62	135	219	354	2.62
Stator Case Ass'y	275	500	775	2.81	210	430	640	3.04
Fan Frame	381	360	741	1.94	381	300	681	1.78
Fan Rotor Ass'y	N/A	N/A	N/A	N/A	1,250*	250	1,500	1.20
Booster Blades	N/A	N/A	N/A	N/A	190	250	440	2.31
	1985							
Nacelle	856	1,200	2,056	2.40	856	1,200	2,056	2.40
Stator Case Ass'y	125	250	375	3.00	125	250	375	3.00
Vane Frame	410	320	730	1.78	410	320	730	1.78
Fan Rotor Ass'y	N/A	N/A	N/A	N/A	1,250*	450	1,700	1.36
Booster Blades	190	250	440	2.31	190	250	440	2.31

*Does Not Include Engine Certification Testing

**Complexity Factor = (Total Development Cost)÷(Engineering Development Cost)

1. All cost figures in $1,000.

Table XLIX. Material Development and Blade Pilot Production Costs.

Material	Rene' 120		(A) NiTac		Tungsten Wire	
Cooling Technology	Advanced Film	Current Film	Advanced Film	Current Film	Advanced Convection & Impingement	Current Film
Material & Process Dev. (not incl. in eng. cost)	0	0	$7 - 10 million		$7 - 10 million	
HPT Blade Pilot Production*, $	400,000	300,000	900,000	700,000	600,000	700,000
LPT Blade Pilot Production*, $						
Convection and Impingement: Stg. 1, $	250,000		600,000		600,000	
Convection and Impingement: Stg. 2, $	250,000		600,000		450,000 (uncooled)	
Total, $	500,000		1,200,000		1,050,000	

* 1st Set of Blades & Mfg. Transition Costs

warranty except in those cases where damage occurred as the result of foreign object ingestion.

The information compiled in-house and in the field indicates that life expectancy of fiber reinforced polymeric composites is equal to metal for secondary structures. It also shows that the level of repair and maintenance is lower in most cases and equal to in all other cases where damage has been experienced by the product during use. Therefore, for the purpose of this study, it has been assumed that there will be no overall cost difference in the maintenance of composite structure versus metal structure.

3.5.5 Cost Comparison Summary

Using the component breakdown defined in Table XII of Section 3.3.8, the development and production costs for the various configurations of both the 1979 and the 1985 engines are summarized in Table L. The development costs are given in dollars and the production costs, for 600 units, are given as a percentage of the appropriate baseline costs.

Table L. Development and Production Costs.

Component	Replacement			Redesign		
	Total Development Cost ($000's)	Production Tooling Cost ($000's)	600th Unit Production Cost (% of Baseline)	Total Development Cost ($000's)	Production Tooling Cost ($000's)	600th Unit Production Cost (% of Baseline)
1979						
Nacelle	2,356	828	71.9	1,811	828	46.1
Spinner	354	25	24.2	354	25	24.2
Stator Case Ass'y	775	560	72.2	640	460	53.8
Fan Frame	741	416	86.0	681	508	65.5
Fan Rotor Ass'y	N/A	N/A	N/A	750	510	41.6
1985						
Nacelle	2,056	1,065	48.0	2,056	1,065	48.0
Stator Case Ass'y	375	200	85.0	375	200	85.0
Vane Frame	730	600	54.2	730	500	45.7
Fan Rotor Ass'y	N/A	N/A	N/A	800	500	27.7
Booster Blades	440	348	20.0	440	348	20.0

3.6 BENEFIT ANALYSIS

Once the cost of each detail component was determined, its effect on the engine selling price was ascertained. This was done through a standard type business plan engine pricing analysis. The input to this analysis consisted of the data discussed in the preceeding sections which consist basically of development costs, tooling costs, and engine shop costs. The business plan pricing analysis then converted these data into a selling price, using data based on past commercial engine programs, taking into account potential sales quantity, amortization of development and tooling, and other costs such as IR&D, G&A, warranty and retrofit, project expense, product support, royalty, rent, reserves and insurance, and profit. The engine selling price was then used as input to the benefit analysis in which the effect each component has on the Direction Operation Cost (DOC) and the Return On Investment (ROI) was evaluated.

3.6.1 Method

The economic benefits of engine or nacelle composite or eutectic turbine alloy substitutions was calculated by converting the resulting weight, cost, and performance engine changes into changes in the base aircraft characteristics.

A baseline aircraft design was defined as summarized in Table LI. This was a GE design based on advanced engine and aircraft technology derived from various ATT contract studies. The design lies within the range of advanced aircraft studied by the aircraft companies but is meant to provide a reasonable basis for trade factors rather than to represent an assessment of aircraft capability. Trade factors for specific changes in engine parameters (Table LII) were then calculated holding payload and range constant and allowing the gross weight to vary as required. Economic ground rules used are consistent with those used in Ref. 3, with the approach being to illustrate the effect of changes in engine parameters associated with each advanced design feature on the change in aircraft economics.

Composite material substitutions were made with no effect on engine SFC (cost and weight changes only). Eutectic turbine alloy substitutions, however, result in cooling flow reductions which result in SFC and engine core size changes for constant thrust. Engine influence coefficients relating turbine cooling flow changes to SFC and engine component sizes are given in Table LIII. Core, booster, and LP turbine weight and cost scaling relationships employed to convert size to weight and cost changes are summarized in Table LIV. The baseline engines at 1979 and 1985 technology levels were sized to the same takeoff thrust, as shown on Table LV.

Table LI. Mission and Aircraft Definition Used in Trade Studies.

Design Range, km (n. mi.)	5556 (3000) n. mi.
Number of Passengers	195
Cruise Mach Number	0.9
A/C and Engine Technology Level	Advanced
TOGW, kgs/lbs	121,109 (267,000) lbs
Number of Engines	3
Rated Thrust per Engine	26,800 lbs
Fuel Cost	25¢/gal.
Other Costs	1973 $

Table LII. Mission Trade Factors* for Engine Parameters.

Change	DOC	ROI (Points)	TOGW	A/C Selling Price	Fuel Usage
1% sfc	0.72%	-0.30	0.71%	0.6%	1.3%
45.4 kg (100 lbs.) wt/eng.	0.19%	-0.09	0.28%	0.24%	0.3%
$10,000 Basic Engine Selling Price	0.17%	-0.09	-	0.25%	-
$10,000 Installation Selling Price	0.07%	-0.06	-	.22%	-
$1/Block Hr. Eng. Parts Repl.	0.34%	-0.14	-	-	-
0.1 Man Hr/Blk Hr. Eng. Maint. Labor	0.22%	-0.09	-	-	-

* Based on constant range & payload, variable gross weight. Derivatives apply to engine of 120,102 N (27,000 lbs.) rated TO thrust.

Table LIII. Cooling Air Effects (Approximate), 1985 Engine Cycle.

Change	Effect on Engine		Merit Factor* Changes		
	sfc	Core Size Req'd	DOC	ROI (Points)	Fuel Usage
+1% HPT Cooling (CDP to HPT Exit)	+0.3%	+1.5%	+.4%	-.2%	+.4%
+1% LPT Cooling (Stg. 6 to LPT Exit)	+0.2%	+1.6%	+.3%	-.2%	+.3%

* Based on 5556 km (3000 n. mi.) design range. Effects larger for longer range A/C.

Table LIV. Engine Scaling.

- Design and cost estimates made in convenient size for each component

- Scaled to common size 120,102 N (27,000 lbs. thrust)

  using following exponents on thrust (or airflow) scale factor.

- sfc	Const.
- Basic engine rotor weight	1.4
- Basic engine static structure at	1.3
- Installation weight	1.0
- Basic engine cost	0.6
- Installation cost	0.8

Table LV. Base Engine Data.

Technology Level	1979	1985
SLS T/O Fn N (lb)	119212 (26800)	119212 (26800)
Bypass Ratio	4.3	7.3
T/O T_4, (^oF)	1371 (2500)	1538 (2800)
Fan Dia., (in.)	1.75 (68.9)	1.75 (68.9)
Fan Flow, kg/sec (lb/sec)	435 (958)	435 (958)
Fan P/P	1.8	1.8
Boost P/P	2.5	2.75
Core Corr. Flow, kg/sec (lb/sec)	35.8 (79.0)	22.8 (50.3)
Core P/P	12.0	14.0

3.6.2 Preparation of Engine Cost Data

Once the cost of each detail component was determined in the 119,212 N (26,800 lb) Fn size, its effect on the total engine cost to the aircraft manufacturer was ascertained. This was done through a standard type business plan engine pricing analysis. The input to this analysis consisted of shop costs, development costs and tooling costs.

The economic factors considered in the pricing analysis are summarzied in Table LVI. Production, development, and tooling costs as well as normal overhead and pricing practices are included in the engine selling price. Engine selling price is subsequently referred to as engine cost in all subsequent tables, viewed as cost to the airframe manufacturer as an input cost to airline investment or operating cost economics.

Other economic factors such as maintenance and parts replacement are included in the DOC by a GE modification of the ATA method.

Depreciation is taken over a 15 year period rather than 12 and 20% engine spares are assumed rather than 40% in the 1967 ATA formula. Also, engine maintenance and materials costs were taken at rates obtained from GE experience which differs from the ATA formula.

3.6.3 Discussion of Results

Results for ΔDOC, ΔROI, ΔA/C selling price, and Δ% fuel saved are given for each element evaluated.

To aid in the appreciation of the magnitudes implied by a 1% DOC saving or a 1% fuel saving, the aggregate saving for a fleet of 100 A/C and 1000 A/C are provided below.

Fleet Size		
Number of aircraft	100	100 (70)
1% Fuel Saving		
Equals cubic meter/year (millions gals/year)	23000 (7)	230000 (70)
1% DOC Saving		
Equals millions $/year	4	40
1% ROI Increase		
Equals an equivalent increase in total discounted cash flow (millions of $) over 14 years life of A/C.	60	600

Table LVI. Engine Economic Factors.

- Engine Pricing
  - Engine Shop Cost (Production Cost)

    Ave. cost estimated for specified no. of units - std. learning curve.

    Related to price by GE procedure.

  - Development & Tooling Costs

    Written off over specified number of engines.

    Does not include materials & component applied research prior to decision to incorporate in engine.

- Engine Maintenance
  - Included in DOC & ROI per specified method.
  - Parts replacement related to engine price.

- Procedure
  - Estimates supplied for above by design and manufacturing.
  - Changes vs. base design are then converted to changes in engine price.
  - Effects on DOC, ROI then determined using mission trade factors.

3.6.4 Economic Benefits - Composite Materials

All design substitutions are made in a size appropriate to either the 1979 or 1985 technology level. The base engine for 1979 technology differs from the 1985 technology engine as indicated in Table LV. A summary of weight and cost changes due to the nacelle and each of the five engine parts considered on a replacement or redesign basis is reproduced in Table LVII.

The economic benefits calculated for the best estimate costs of Table LVII are given in Tables LVIII through Table LXIII for each of the substitutions. The summary of ΔDOC improvements in Table LXIV shows that composites in the nacelle has the largest payoff with the fan rotor in second place. Total potential gains vary from 2.8% to 4.6% for the various cases studied.

3.6.5 Economic Benefits - Eutectic and Tungsten Wire Superalloy Turbine Alloys

The economic benefits of substituting advanced NiTac or tungsten wire-superalloy for R120 in the single stage high pressure turbine are summarized in Tables LXV and LXVI. The benefits are calculated for two levels of design bulk temperature increase, +83°C (+150°F) and +167°C (+300°F), and with no blade cost differences assumed. The magnitude of the bulk temperature which can be achieved considering all limiting factors is uncertain and results are therefore presented to cover the range of possibilities for the two advanced materials. Several levels of turbine blade cooling technology were also assumed for the comparison. There will be a problem in putting holes in either of the advanced materials and more important in coating the inside of the holes. Therefore, results are provided with and without restrictions on the use of cooling holes.

The results of substituting advanced turbine materials in the low pressure turbine are given in Table LXVII, also for no blade cost difference and for convection and impingement cooling.

3.6.6 Sensitivity Study - Composite Materials

Since there is some uncertainty, due to the developmental stage of the state-of-the-art, as to the level of cost achievable with composite materials and construction, a sensitivity study was performed to evaluate various cost ranges.

In the area of material costs, the prices for the prepreg materials selected for consideration in this study were based on a substantial reduction in fiber and prepreg process costs during the 1974 to 1985 time period. These prices are possible

Table LVII. Composite Materials Cost and Weight Benefits.

All weight & cost data in common size, engine SLS T/O Fn = 119,212 newtons (26800 lbs.)
Costs in 1973 $1000, Avg. of 2000 engines

		Base			Replacement			Redesign		
		Weight kg	Weight lb.	Cost, 1000$	Weight (ΔWt.) kg	Weight (ΔWt.) lb.	ΔCost, 1000$	Weight (ΔWt.) kg	Weight (ΔWt.) lb	ΔCost, 1000$
1979	Nacelle	1195	2634	Base	938 (-257)	2067 (-567)	-156	920 (-274)	2029 (-605)	-156
	Spinner	23	50		20 (-2)	45 (-5)	-7	16 (-6)	36 (-14)	-8
	Stator Assy.	229	505		131 (-98)	288 (-217)	+2	121 (-107)	266 (-239)	-29
	Fan Frame	213	469		127 (-86)	279 (-190)	+7	115 (-98)	253 (-216)	-10
	Fan Rotor Assy.	185	407		-	-	-	141 (-44/-68*)	310 (-97/-149*)	-33
	Booster Blades	14	31		9 (-5)	20 (-11)	-4	9 (-5)	20 (-11)	-4
1985	Nacelle	990	2182		799 (-191)	1761 (-421)	-173	747 (-243)	1646 (-536)	-173
	Stator Assy.	78	171		41 (-36)	91 (-80)	-8	41 (-36)	91 (-80)	-8
	Fan Frame	240	530		182 (-59)	401 (-129)	-15	160 (-74)	367 (-163)	-20
	Fan Rotor Assy.	185	407		-	-		130 (-54/-124*)	287 (-120/-274*)	-47
	Booster Blades	8	17		5 (-3)	11 (-6)	-3	5 (-3)	11 (-6)	-3

* With containment credit

Table LVIII. Economic Benefits of Composite Nacelle.

Technology	1979		1985	
	Replacement	Redesign	Replacement	Redesign
Δ DOC, %	-2.17	-2.24	-2.01	-2.23
Δ ROI, Points	+1.46	+1.50	+1.43	+1.53
Δ A/C Selling Price, %	-4.75	-4.84	-4.76	-5.04
Δ Fuel Used, %	-1.70	-1.81	-1.26	-1.61

Table LIX. Economic Benefits of Composite Fan Rotor Assembly.

Technology	1979		1985	
	Replacement	Redesign	Replacement	Redesign
Δ DOC, %		-.70/-.80		-.98/-1.27
Δ ROI, Points		+.37/+.42		+.52/+.66
Δ A/C Selling Price, %		-.94/-1.06		-1.21/-1.68
Δ Fuel Used, %		-.29/-.44		-.36/-.82

/ includes containment reduction allowable with composite fan blade.

Table LX. Economic Benefits of Composite Fan Frame.

Technology	1979		1985	
	Replacement	Redesign	Replacement	Redesign
Δ DOC, %	-.25	-.56	-.48	-.63
Δ ROI, Points	+.12	+.28	+.25	+.32
Δ A/C Selling Price, %	-.31	-.73	-.64	-.82
Δ Fuel Used, %	-.56	-.65	-.39	-.49

Table LXI. Economic Benefits of Composite Fan Stator Assembly.

Technology	1979		1985	
	Replacement	Redesign	Replacement	Redesign
Δ DOC, %	-.38	-.91	-.27	-.27
Δ ROI, Points	+.18	+.48	+.13	+.13
Δ A/C Selling Price, %	-.47	-1.19	-.35	-.35
Δ Fuel Used, %	-.65	-.71	-.24	-.24

Table LXII. Economic Benefits of Composite Spinner.

Technology	1979		1985	
	Replacement	Redesign	Replacement	Redesign
Δ DOC, Points	-.12	-.15		
Δ ROI, Points	+.06	+.08		
Δ A/C Selling Price, %	-.17	-.21		
Δ Fuel Used, %	-.02	-.04		

Table LXIII. Economic Benefits of Composite Booster Blades.

Technology	1979		1985	
	Replacement	Redesign	Replacement	Redesign
Δ DOC, %	-.08	-.08	-.06	-.06
Δ ROI, Points	+.04	+.04	+.03	+.03
Δ A/C Selling Price, %	-.11	-.11	-.08	-.08
Δ Fuel Used, %	-.03	-.03	-.02	-.02

Table LXIV. Composite Materials Benefits, Summary.

Technology	Δ DOC vs. Base Metal Design			
	1979		1985	
	Repl.	Redesign	Repl.	Redesign
Nacelle	-2.17	-2.24	-2.01	-2.23
Fan Rotor	-	-.70 (-.80)*	-	-.98 (-1.27)*
Fan Frame	-.25	-.56	-.48	-.63
Fan Stator	-.38	-.91	-.27	-.27
Spinner	-.12	-.15	-	-
Booster	-.08	-.08	-.06	-.06
Total	-3.0 %	-4.6 %	-2.8 %	-4.2 %

* With containment credit

Table LXV. Benefits of Eutectic Material in High Pressure Turbine Blade.

(Not including blade cost differences)

Cooling Technology Level	Current Technology Film			Adv. Film		
Blade Material	R120	Advanced NiTac		R120	Advanced NiTac	
ΔT Capability, ^oC (^oF)	Base	+83 (+150)	+167 (+300)		+83 (+150)	+167 (+300)
No. Engines	2000					
T_4, ^oC (^oF)	1538 (2800)					
Δ DOC, %	Base	-.85	-1.23	Base	-.37	-.66
Δ ROI Points		+.40	+.60		+.17	+.31
Δ A/C Selling Price, %		-.98	-1.46		-.43	-.76
Δ Fuel Used, %		-1.02	-1.51		-.45	-.79

Table LXVI. Benefits of Tungsten Wire Composite Material in High Pressure Turbine Blade.

(Not including blade cost differences)

Cooling Tech. Level	Current Tech. Film	Conv. & Imp.		Current Film		Adv. Film	Conv. & Imp.		Current Film	
Blade Material	R120	Tungsten Wire				R120	Tungsten Wire			
Δ T Capability, °C (°F)	Base	+83 (+150)	+167 (+300)	+83 (+150)	+167 (+300)	Base	+83 (+150)	+167 (+300)	+83 (+150)	+167 (+300)
No. Engines	2000									
T_4, °C (°F)	1538 (2800)									
Δ DOC, %	Base	-.05	-.84	-.80	-1.28	Base	+.88	+.09	+.12	-.36
Δ ROI, Points		+.02	+.39	+.37	+.60		-.41	-.04	-.06	+.17
Δ A/C Sell. Price, %		-.05	-.95	-.91	-1.46		+1.01	+.10	+.14	-.40
Δ Fuel Used, %		-.05	-.99	-.95	-1.51		+1.06	+.12	+.16	-.41

Table LXVI. Benefits of Tungsten Wire Composite Material in High Pressure Turbine Blade (Concluded).

(Not Including Blade Cost Differences)

Cooling Tech. Level	Adv. Film →		
Blade Material	R120	Tungsten Wire	Superalloy
Δ T Capability, °C (°F)	Base	+83 (+150)	+167 (+300)
No. Engines	2000 →		
T_4, °C (°F)	1538 (2800) →		
Δ DOC, %	Base	-.34	-.63
Δ ROI, Points	↓	+.16	+.29
Δ A/C Sell. Price, %	↓	-.36	-.67
Δ Fuel Used, %	↓	-.39	-.74

Table LXVII. Economic Effects of Advanced Material Utilization in Low Pressure Turbine Blades, Stages 1 and 2 (Not Including Blade Cost Differences).

Blade Material	R120	Advanced NiTac		Tungsten Wire	
ΔT Capability, ^{o}C (^{o}F)	Base	+83 (+150)	+167 (+300)	+83 (+150	+167 (+300)
Cooling Technology	Convection & Impingement →				
No. Engines	2000 →				
T_4, ^{o}C (^{o}F)	1538 (2800) →				
Δ DOC, %	Base	-.64	-1.05	-.64	-1.03
Δ ROI Points	↓	+.31	+.50	+.31	+.50
Δ A/C Selling Price, %	↓	-.78	-1.27	-.77	-1.25
Δ Fuel Used, %	↓	-.68	-1.11	-.67	-1.09

Table LXVIII. Advanced Materials Benefits, Summary (Not Including Blade Cost Differences).

Blade Material	Base R120			Tungsten Wire	
Δ T Capability, $^{o}C/^{o}F$	Base	+83 (+150)	+167 (+300)	+83 (+150)	+167 (+300)
Δ DOC, %, LPT Stgs 1 & 2	Base	-.64	-1.05	-.64	-1.03
Cooling Technology	Convection & Impingement →				
Δ DOC, %, HPT	Base	-.85	-1.23	-.80	-1.28
Cooling Technology	Current Film →				
Δ DOC, % Total	Base	-1.49	-2.28	-1.44	-2.31

if basic material and process trends continue as they have been over the past few years. However, the effect of inflation and energy crisis factors on these trends are difficult to measure accurately. A judgement was made on the likely variation in these costs based on the best information on future costs for prepreg that is available at this time. This information is presented in Figures 43 and 44 for the 1979 and 1985 time periods respectively.

In the area of manufacturing costs, data from materials and process development programs and from composites production at General Electric in Cincinnati, Ohio and Albuquerque, New Mexico, have been used in making a judgement on cost estimates described herein for composites in the 1979 and 1985 time period. By this time, additional knowledge on materials and processes will have been gained, and more sophisticated tooling and equipment will undoubtedly have been introduced and be in operation. These assumptions have not been considered in making the cost estimates. However, the following factors have influenced the judgements made in establishing the confidence level of the cost values that have been projected for the 1979 and 1985 composite designs. These factors are:

1. Firmness of design
2. Accuracy of material cost projections
3. Accuracy of learning curve
4. Process refinement

The above factors are not well defined at this 1974 period. Because of this, a confidence level of 80% has been placed on the cost estimates made for the composites planned for 1979, and a confidence level of 60% has been established for the cost estimates made on the composites described for 1985. The level of confidence projected for both time periods is shown in the curves on Figures 45 and 46.

Other sensitivity factors not considered in the confidence levels shown for the composites include:

1. Effect of labor demands
2. Availability of skilled manpower
3. Energy crisis
4. Others

These factors could significantly alter the cost of manufacturing the many composites considered in the cost and benefits study. However, the ratio of cost to percent confidence would still be the same relative value.

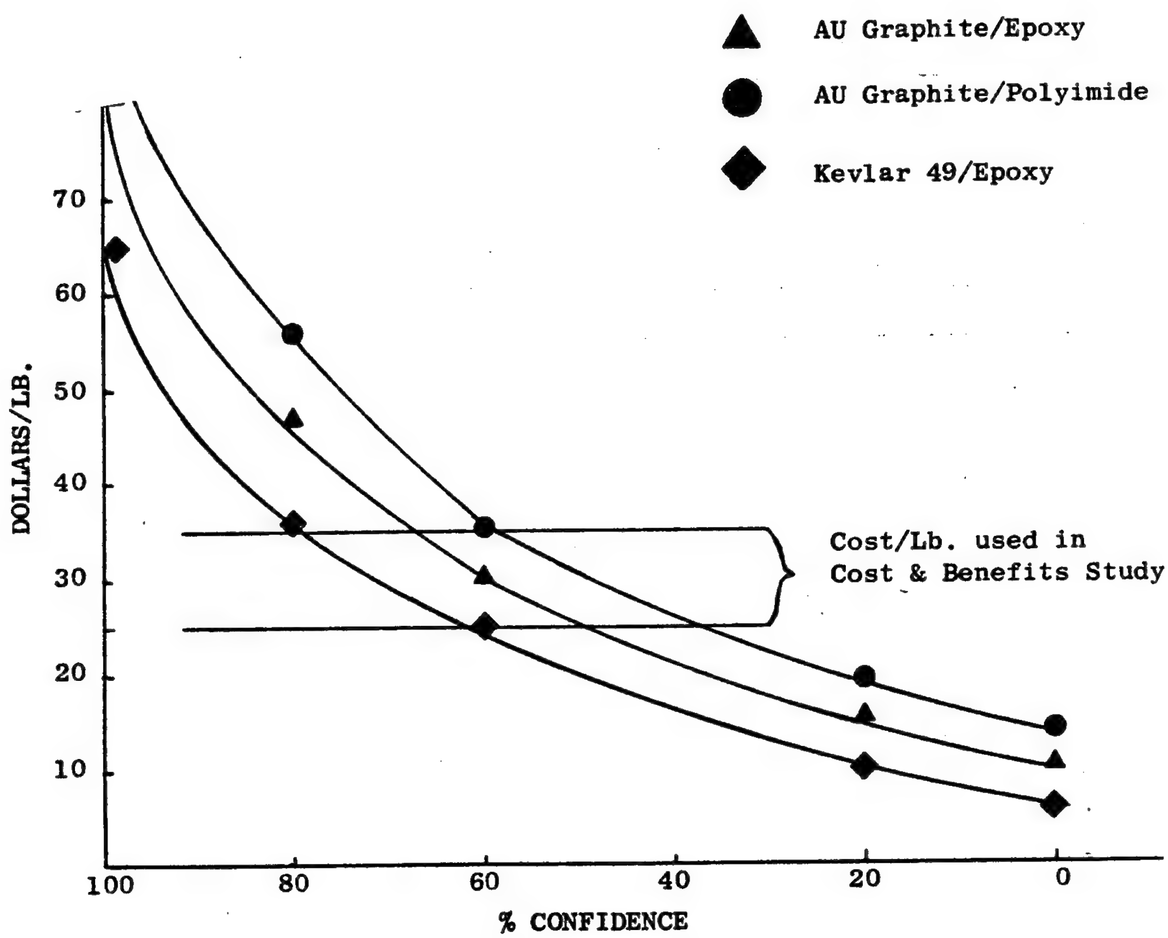


Figure 43. 1979 - Cost of Prepreg.

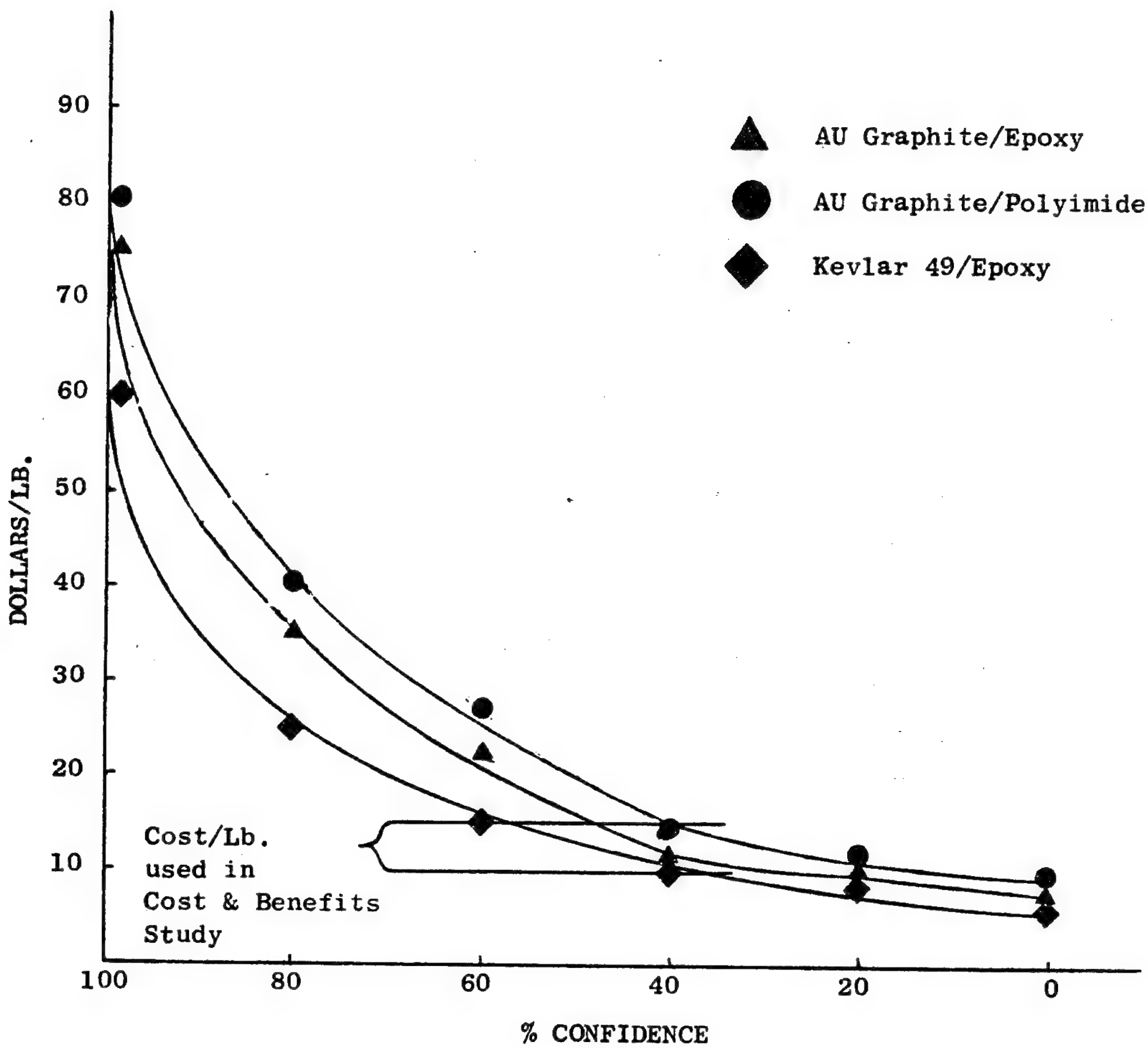


Figure 44. 1985 - Cost of Prepreg.

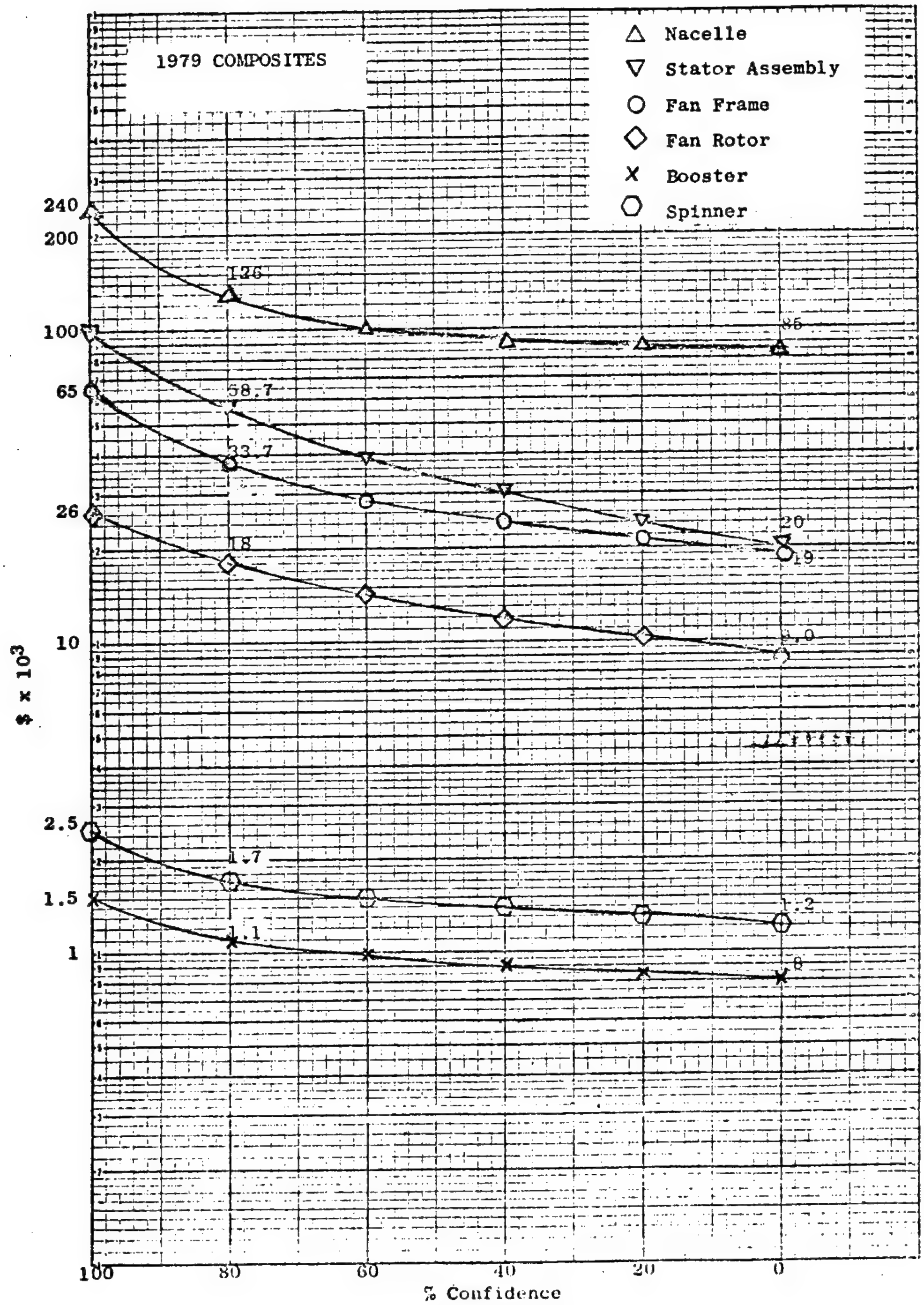


Figure 45. 1979 Composites.

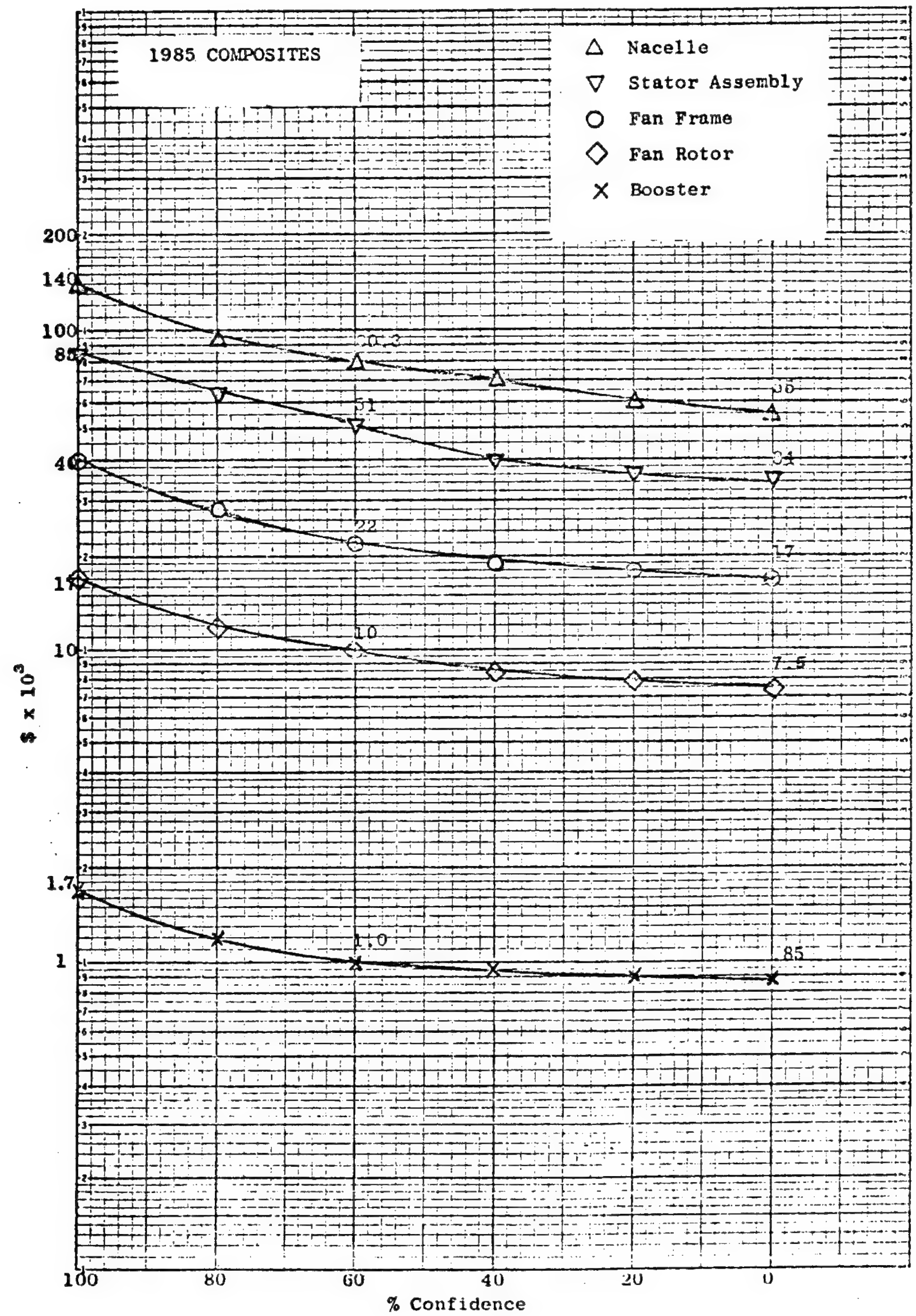


Figure 46. 1985 Composites.

Based on the above information, the effects of a range of cost estimates are given in Figures 47 through 50. If the highest cost estimate is assumed for the fan frame, in 1979 technology, for example, then no economic benefit results. The two parts having the largest potential gain, the nacelle and fan rotor, show a net gain even for the highest cost estimate.

The effect of the engine production volume was also investigated as shown in Figure 51. All data in the basic economic benefit analysis was computed on the basis of a 2000 engine production. If the number of engines produced is reduced to 1000, the economic benefit increases because the engine costs are higher and as a result savings for composite substitutions are greater when expressed in a percentage.

3.6.7 Sensitivity Study - Eutectic and Tungsten Wire/Superalloy Turbine Alloys

The advanced blade materials will cost more than current materials but, at this stage of development, it is not possible to estimate the magnitude of the increase. The effect of relative cost of the advanced NiTaC and tungsten wire-superalloy for the economic benefits of their employment in the high pressure turbine are shown in Figures 52 through 57. A range of cost estimates based on changing the materials plus casting (or layup) costs by a factor of two to ten is illustrated. The remainder of the blade cost (machining, drilling and inserts) is assumed to be a function of cooling technology and not the material.

Similar results are shown in Figures 58 and 59 for the low pressure turbine.

The effect of engine production volume is shown in Figure 60. The increased DOC payoff shown for 1000 engines vs. 2000 engines at a blade cost ratio of 2 is due, as in the case of the composites, to the higher unit engine cost. At a blade cost ratio of two the economic benefit in a 2000 engine production run is greater than in a 1000 engine run because the engine cost increase due to eutectic alloys is reduced as engine costs decrease with production volume.

The results of this study clearly show that the cost of the advanced material must be kept within reason if an improvement in DOC or ROI is to be obtained. For example, if the "casting" cost is 2 or 4 times that of the base material and the HPT blade design is current film cooling (all cases), the following improvements in DOC are obtained vs. the current DOC

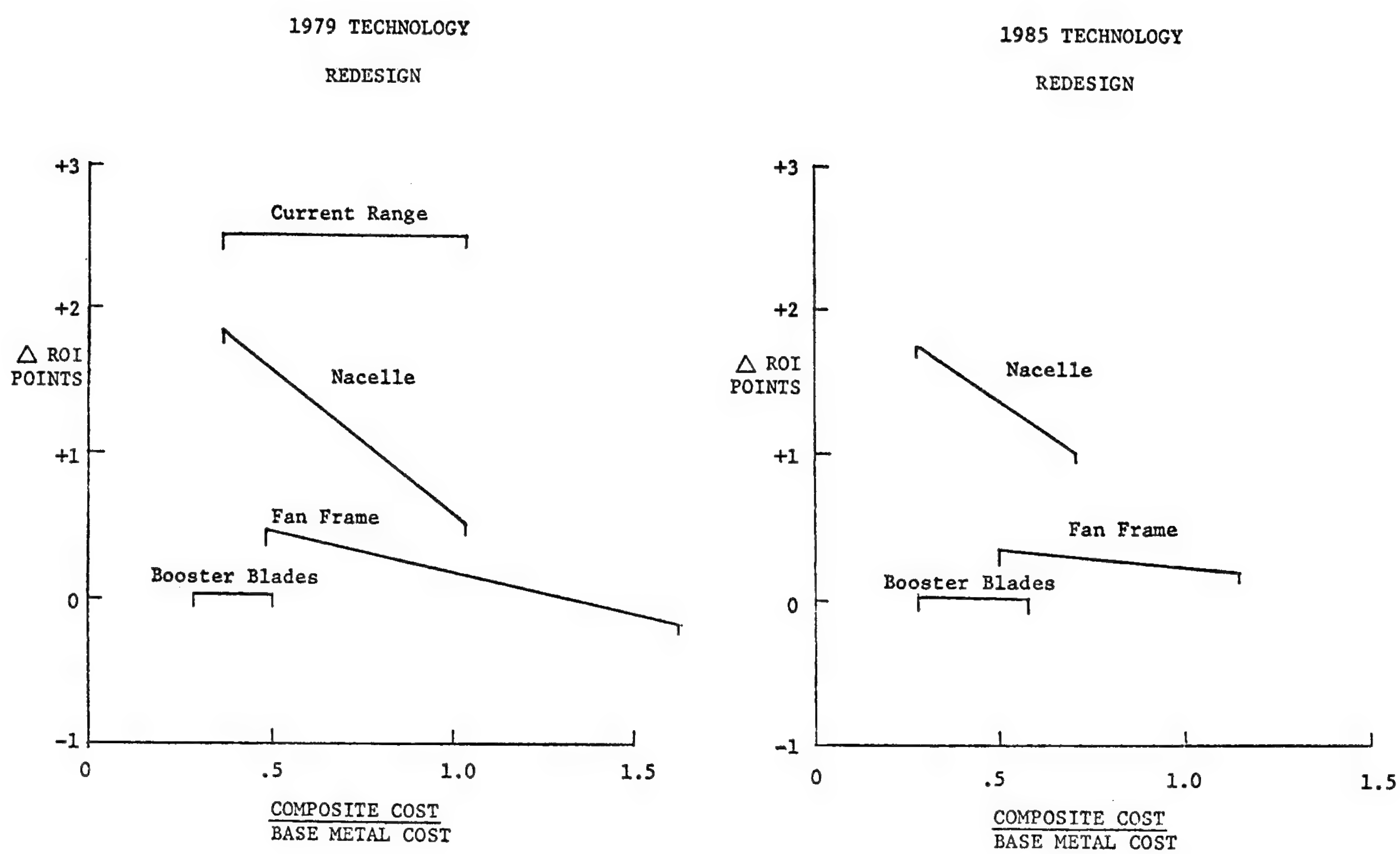


Figure 47. Effect of Parts Cost Estimate on ΔROI Results.

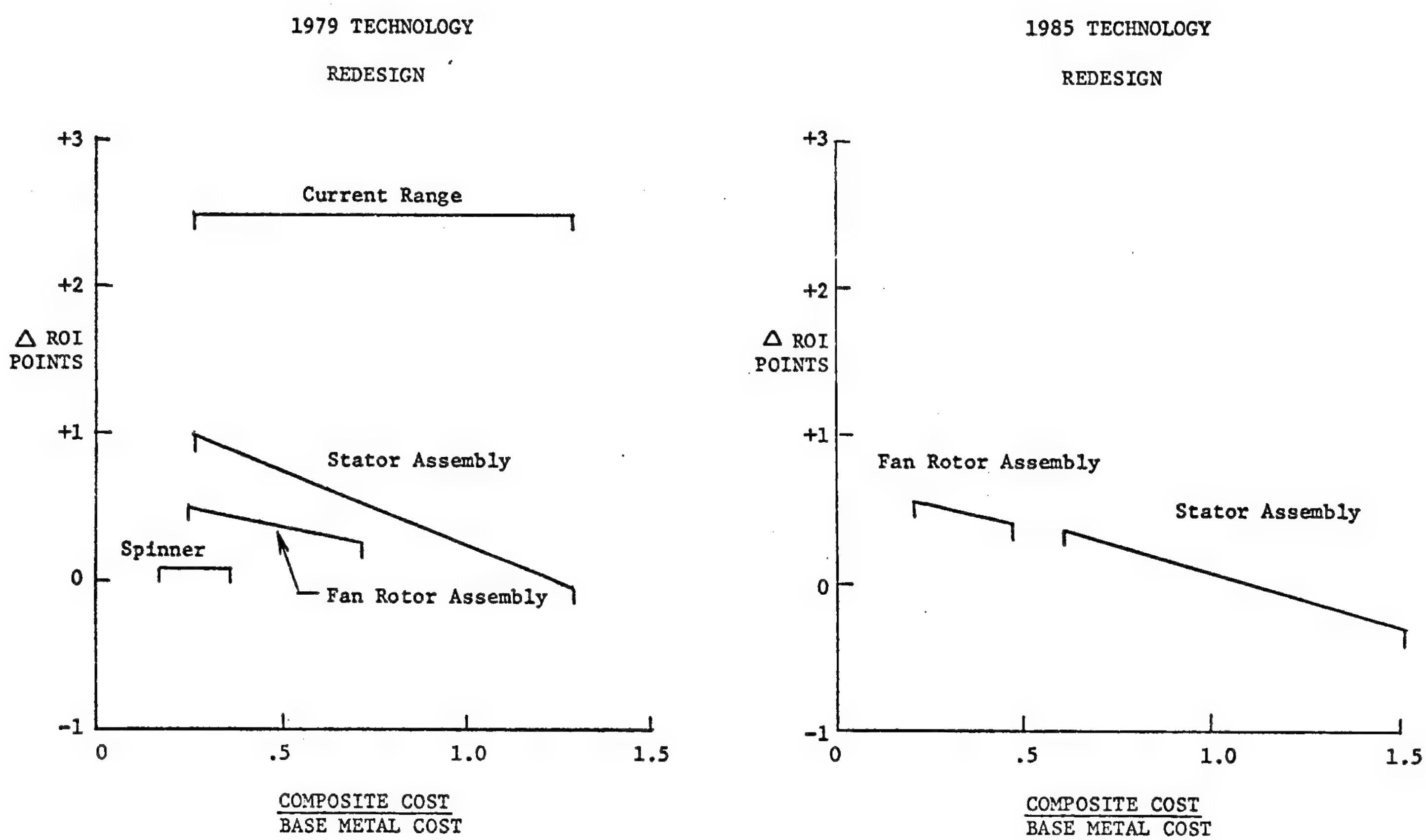


Figure 48. Effect of Parts Cost Estimate on ΔROI Results.

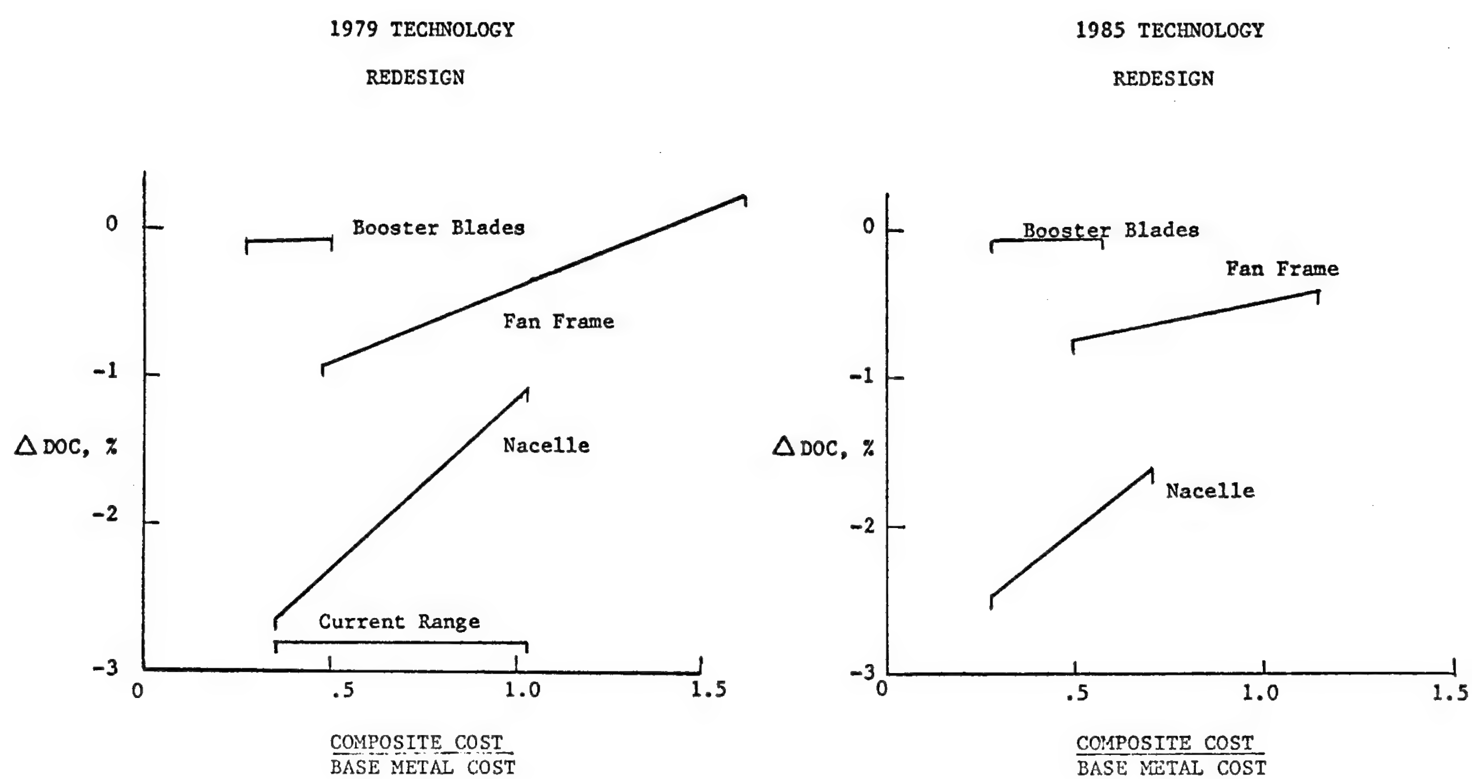


Figure 49. Effect of Parts Cost Estimate on ΔDOC Results.

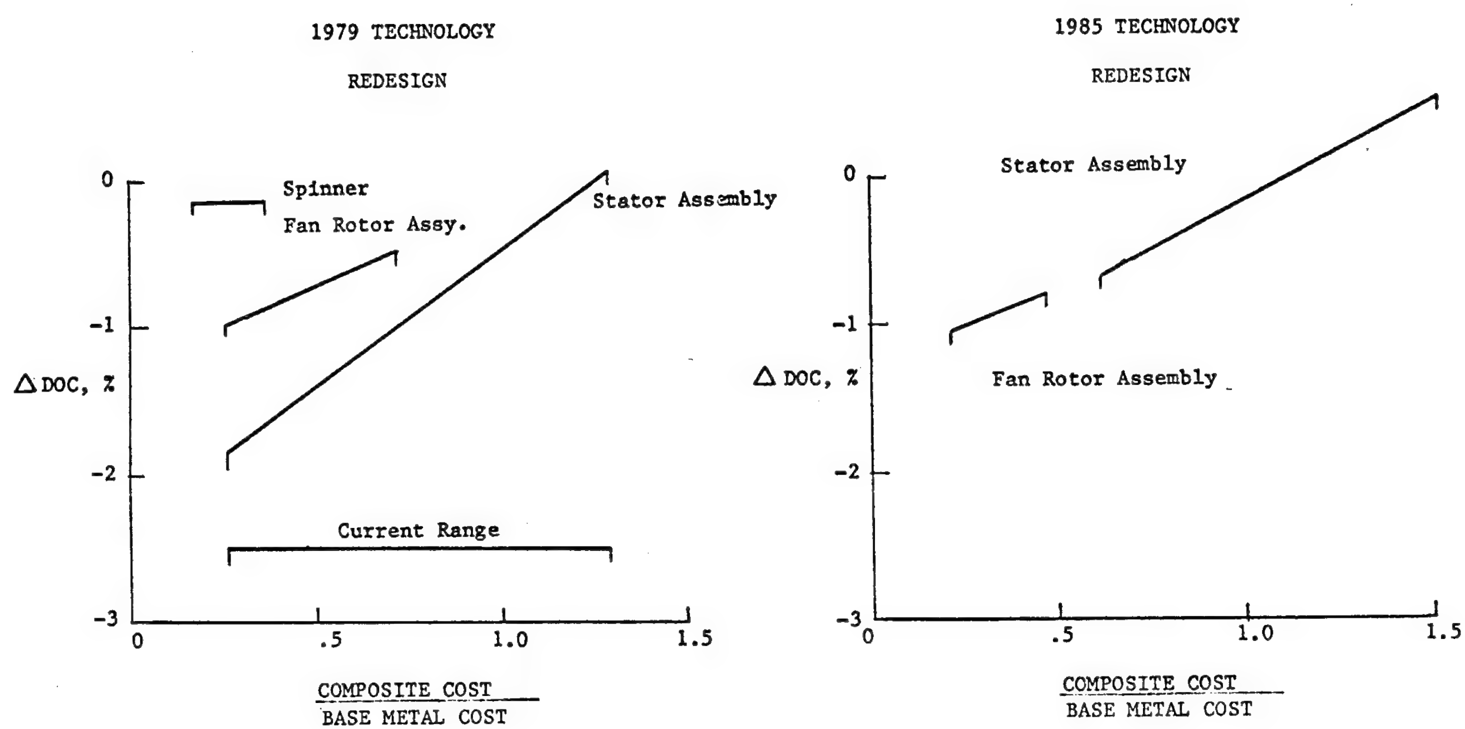


Figure 50. Effect of Parts Cost Estimate on ΔDOC Results.

NACELLE 1979 TECHNOLOGY

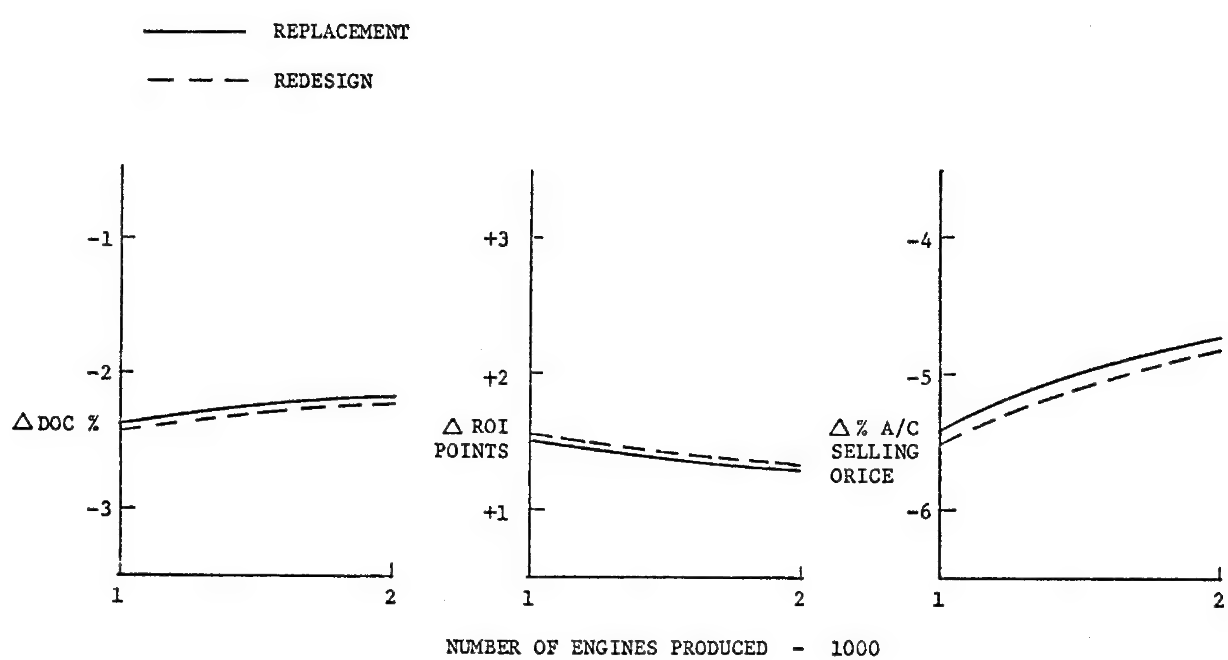


Figure 51. Sensitivity of Economic Benefits to Number of Engines Produced.

Material ΔT	4 x Casting Cost 83°C (+150°F)	4 x Casting Cost 167°C (+300°F)	2 x Casting Cost 83°C (+150°F)	2 x Casting Cost 167°C (+300°F)
ΔDOC due to HP (current film cooling)	-.5%	-.95%	-.75%	-1.2%
ΔDOC due to LPT (convection plus impingement)	-.1%	-.55%	-.5%	-.9%
Total ΔDOC	-.6%	-1.50%	-1.25%	-2.1%

The above suggests that a 4:1 casting cost should be the minimum objective depending upon how much ΔT capability is achieved. If more elaborate cooling is employed on the HPT, the cost objective should be lower although the advanced cooling will be a cost factor itself.

The above results apply to an advanced engine in a new aircraft designed for a 5556 km (3000 n. mi.) range. It should be noted that for a longer range aircraft 10,186 km (5500 n.mi.) being the usual requirement for intercontinental A/C), the advantages of reduced cooling air and its effect on engine performance will be greater. In the case of growth of an existing engine, the situation is much different. Here the incentive is normally to achieve an increase in thrust for a given set of hardware. The advanced turbine material will allow a reduction in cooling air which means that a given increase in thrust can be achieved with a lower turbine temperature or a higher thrust achieved (with appropriate attention to other limiting parts) for a given turbine temperature. Depending upon the limitations of other engine parts, it may prove economical to go to the advanced turbine material in spite of its higher cost to achieve the required thrust.

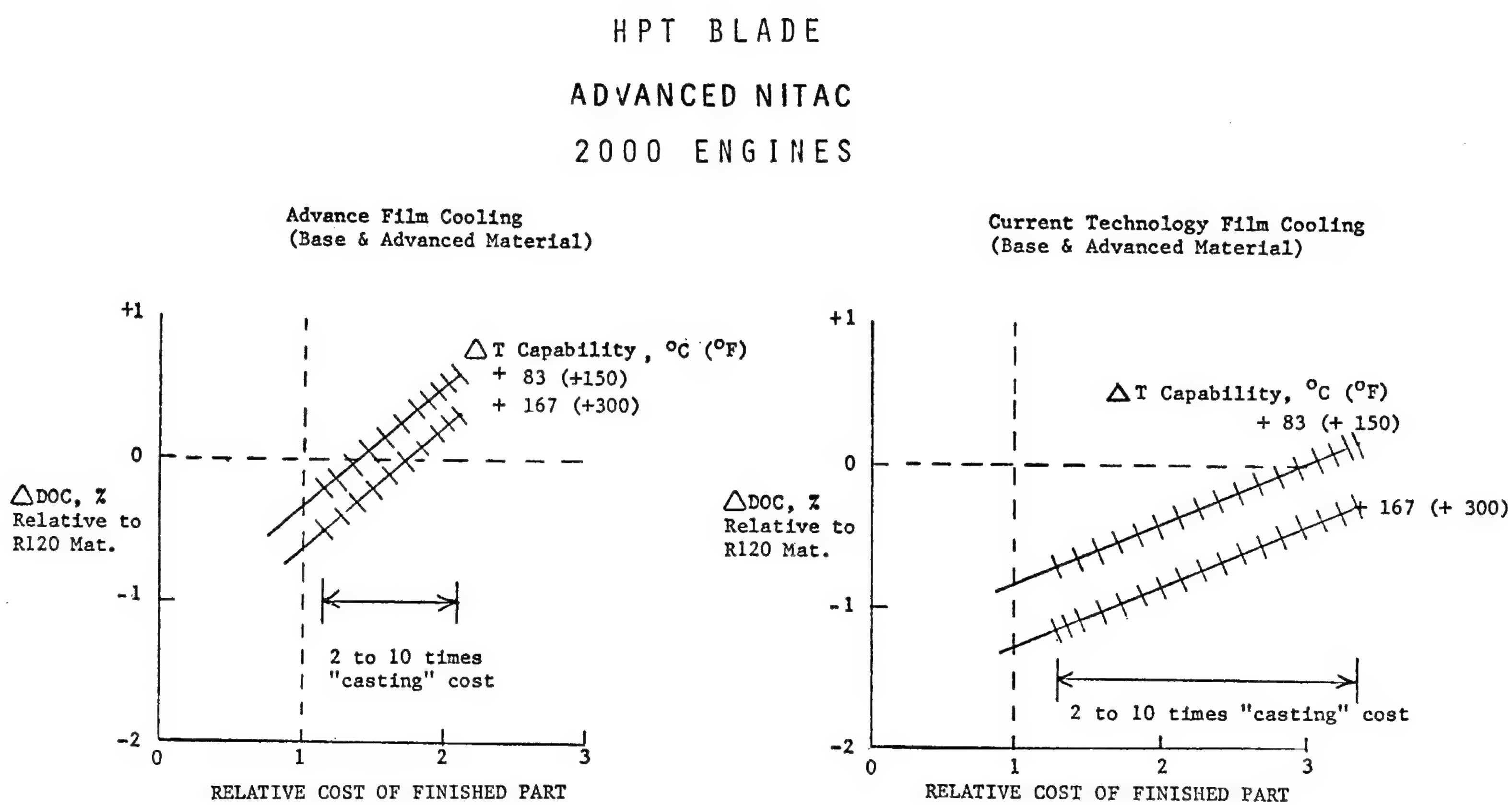


Figure 52. Effect of Blade Cost on Advanced Turbine Material Benefit.

HPT BLADE

ADVANCED NITAC 2000 ENGINES

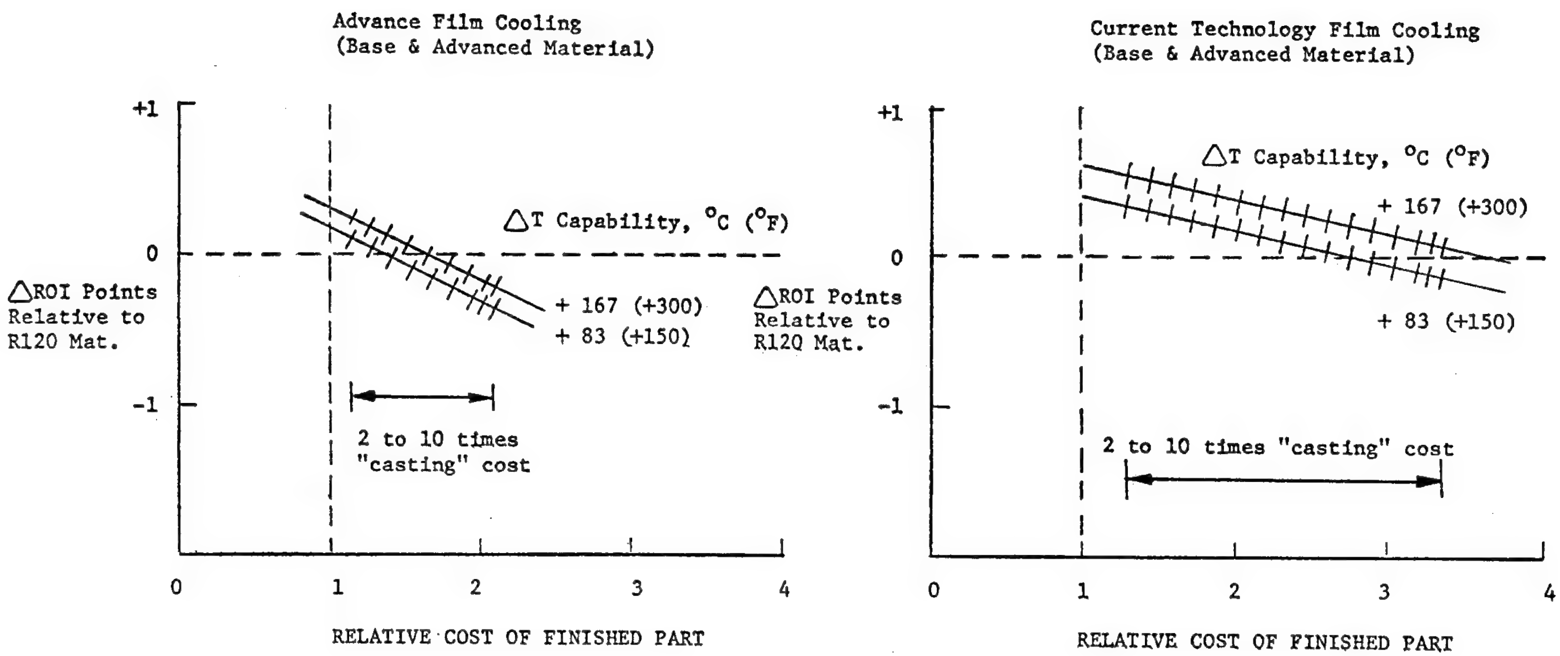


Figure 53. Effect of Blade Cost on Advanced Turbine Material Benefit.

HPT BLADE

TUNGSTEN WIRE

WITH CONVECTION & IMPINGEMENT COOLING

2000 ENGINES

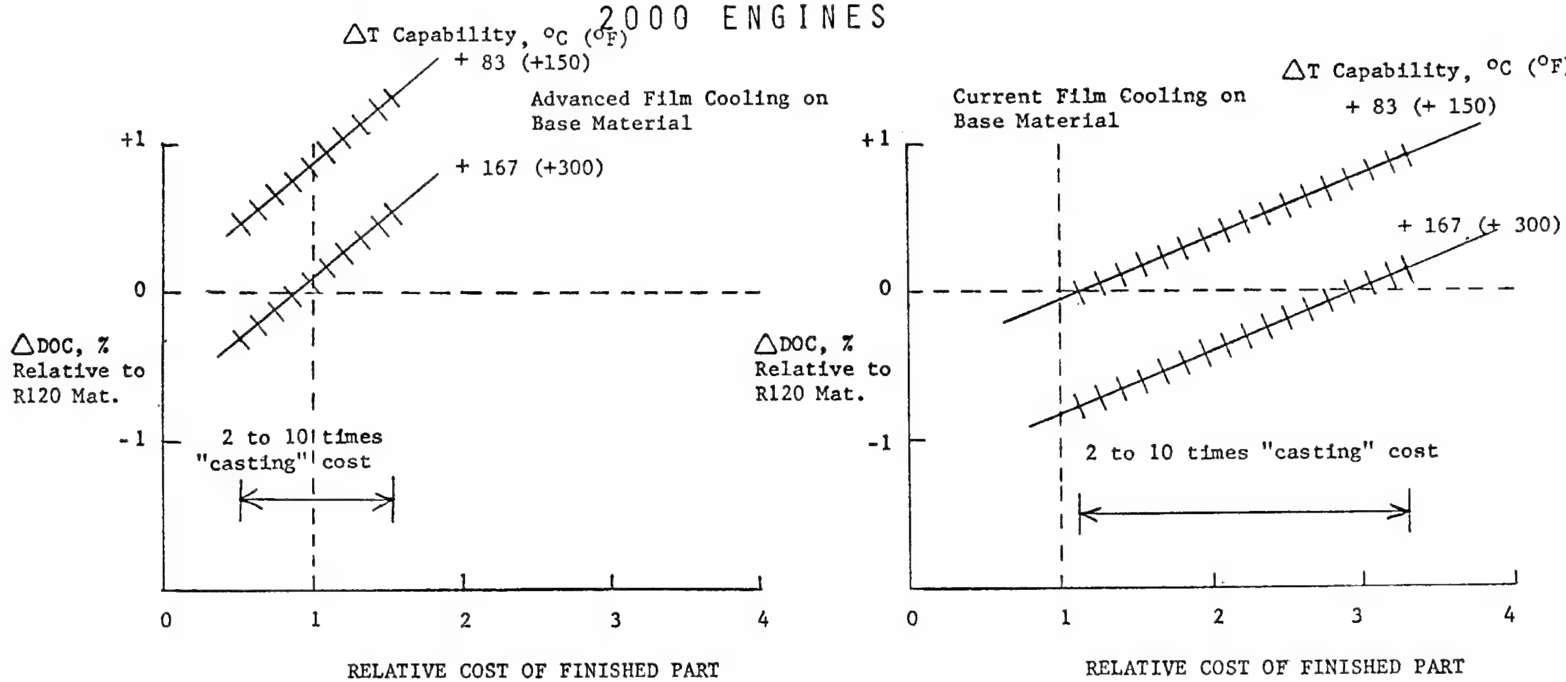


Figure 54. Effect of Blade Cost on Advanced Turbine Material Benefit.

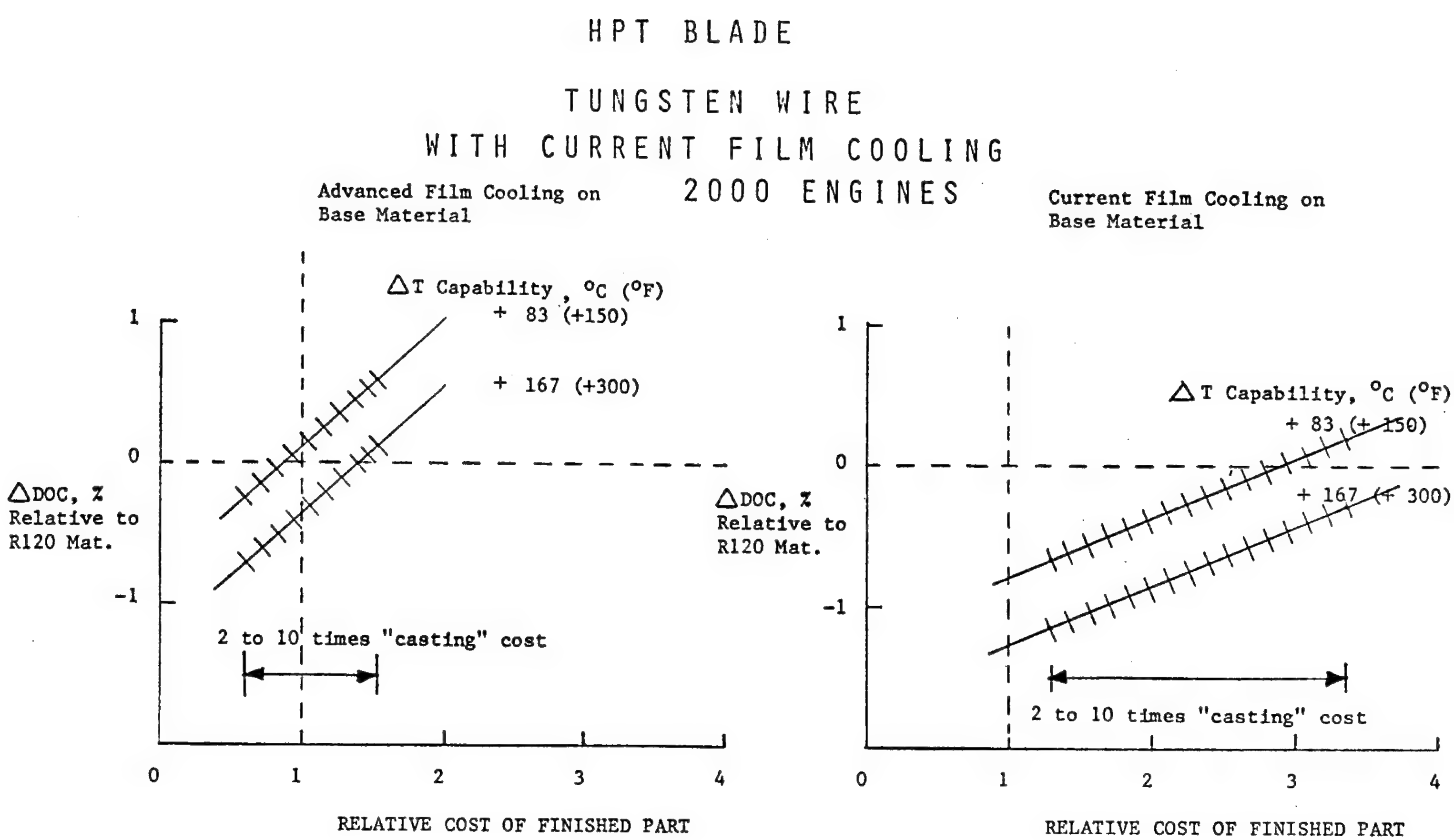


Figure 55. Effect of Blade Cost on Advanced Turbine Material Benefit.

HPT BLADE

TUNGSTEN WIRE
WITH CURRENT FILM COOLING
2000 ENGINES

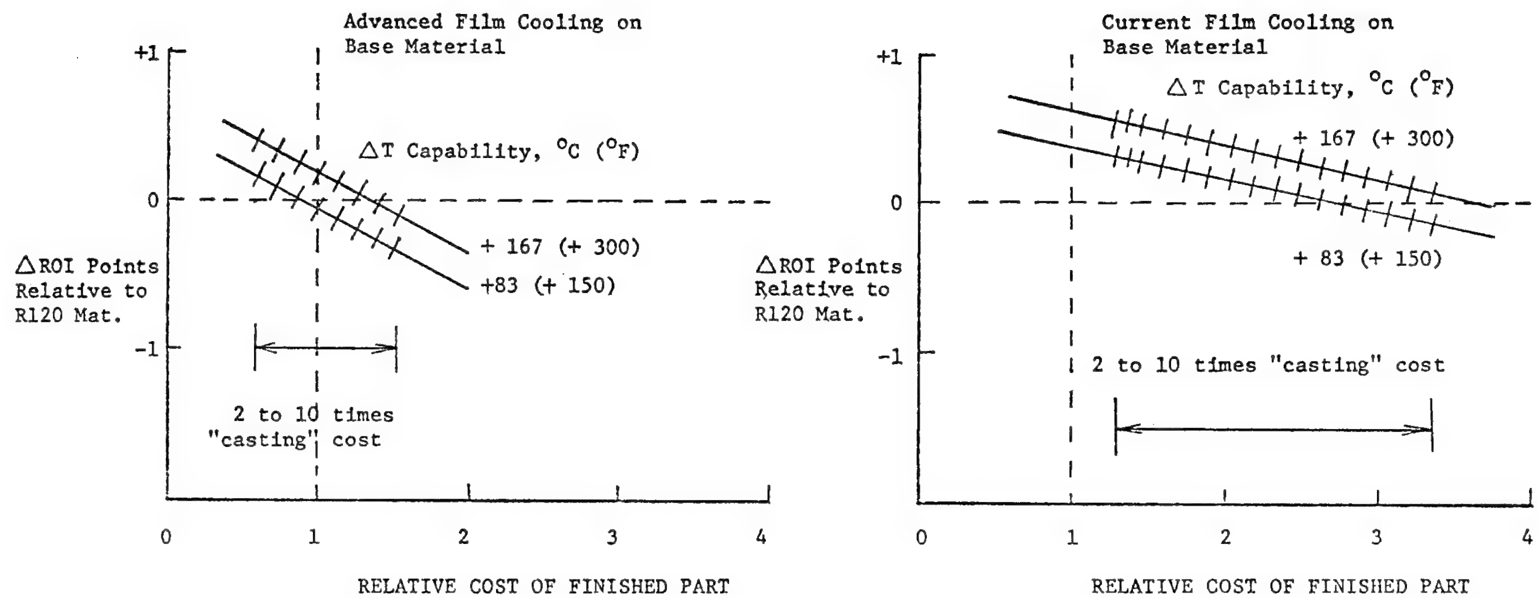


Figure 56. Effect of Blade Cost on Advanced Turbine Material Benefit.

HPT BLADE

TUNGSTEN WIRE
WITH CONVECTION & IMPINGEMENT COOLING
2000 ENGINES

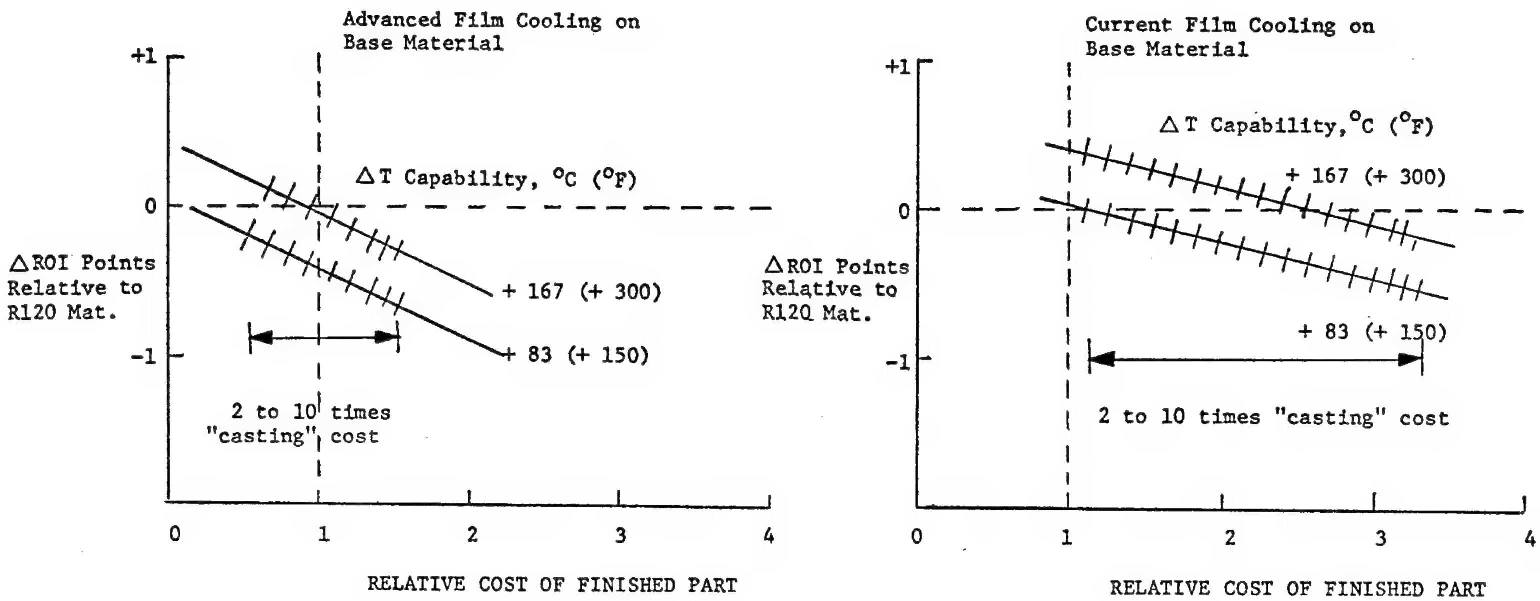


Figure 57. Effect of Blade Cost on Advanced Turbine Material Benefit.

LPT BLADES (2 STAGES, ONLY 1 COOLED FOR 167°C (300°F) ΔT)
ADVANCED NITAC

CONVECTION AND IMPINGEMENT
(BASE AND ADVANCED MATERIAL)
2000 ENGINES

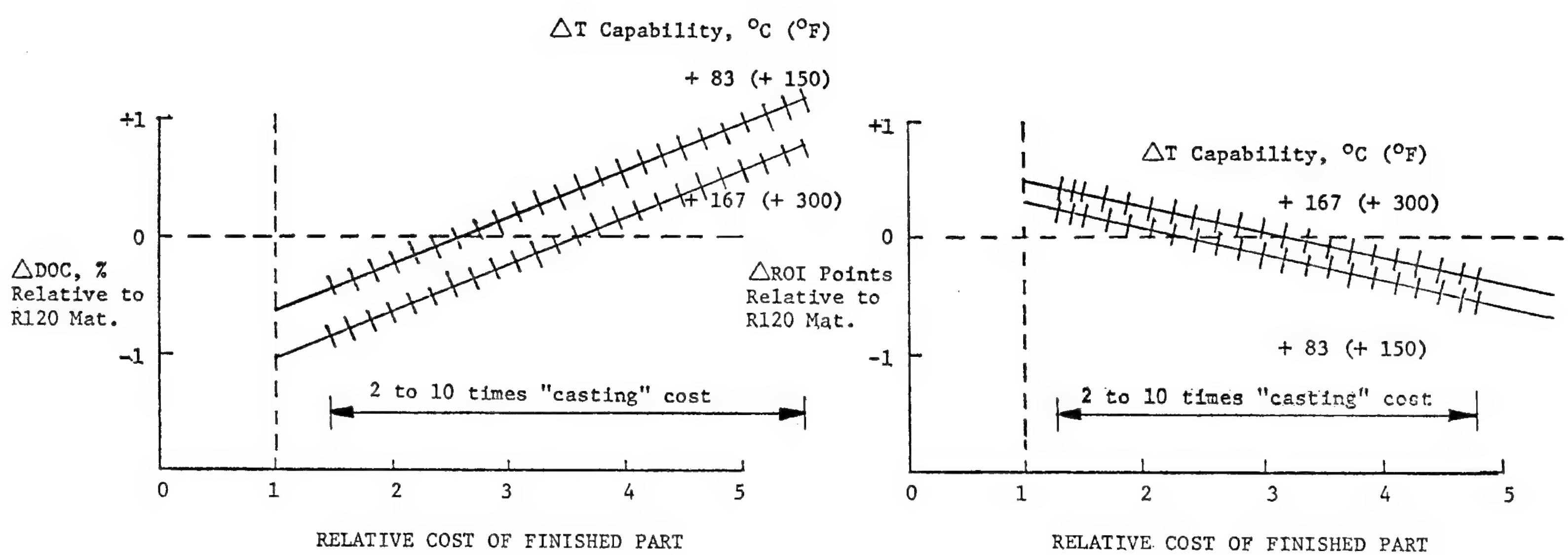


Figure 58. Effect of Blade Cost on Advanced Turbine Material Benefit.

LPT BLADES (2 STAGES, ONLY 1 COOLED FOR 167°C (300°F) ΔT)

TUNGSTEN WIRE
CONVECTION AND IMPINGEMENT
(BASE AND ADVANCED MATERIAL)
2000 ENGINES

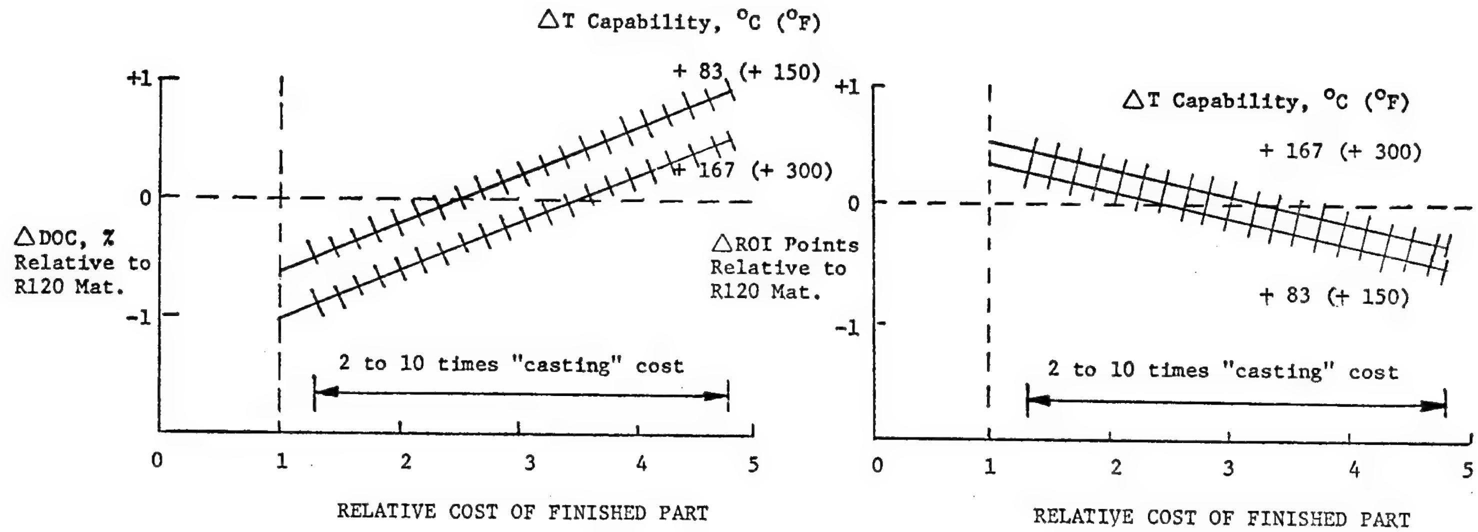


Figure 59. Effect of Blade Cost on Advanced Turbine Material Benefit.

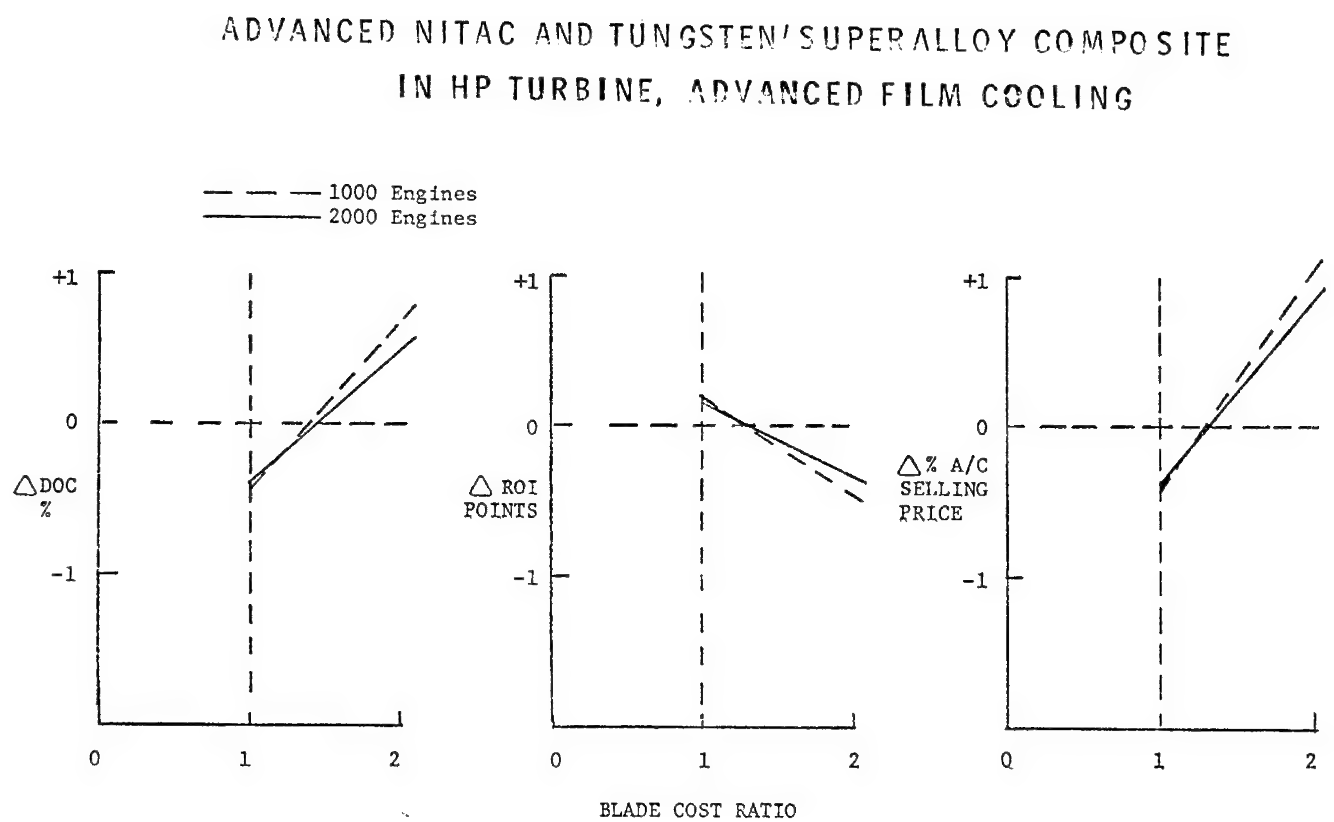


Figure 60. Sensitivity of Economic Benefits to Number of Engines Produced.

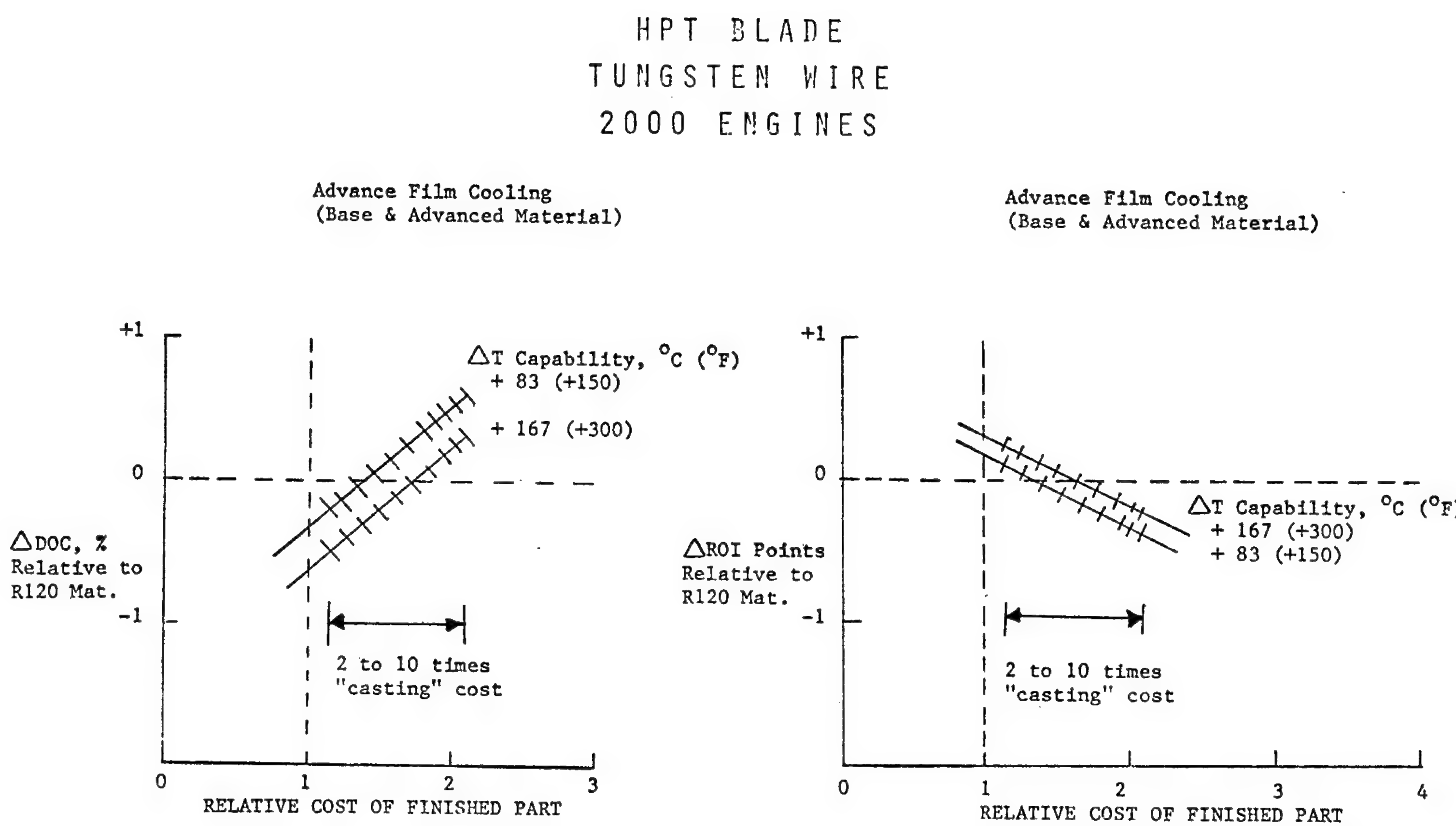


Figure 61. Effect of Blade Cost on Advanced Turbine Material Benefit.

4.0 CONCLUSIONS

The conclusions reached during this program are summarized below and are based on the information shown and discussed in Section 3. The expected overall conclusion, that the use of polymeric composites in appropriate areas of advanced high bypass turbofan engines will result in both a weight and cost savings, was verified. In the turbine area the potential performance benefits available through the use of advanced eutectics and tungsten wire superalloy composites were demonstrated. The major value of the program was in identifying these components which showed the greatest benefit through the use of these materials and of quantifying these benefits. The more specific conclusions that can be drawn from this program are:

1. The two major engine components which showed potential for the most dramatic relative improvement in both weight and cost were the fan frame and the fan rotor assembly.

   A composite fan frame would provide a weight savings ranging from 24 percent to an impressive 46 percent and a cost savings ranging from 14 percent to 54 percent, depending on the engine studied. Scaled to a common engine size, this represents weight savings ranging from 58 Kg (124 pounds) for the 1985 replacement version to 99 Kg (217 pounds) for the 1979 redesigned frame. The lesser total weight savings for the 1985 engines are due to the lighter metal baseline design assumed for that time period. These improvements result in a decrease in DOC ranging from 0.25 percent to 0.63 percent and a fuel savings ranging from 0.39 percent to 0.65 percent. As could be expected, the most benefits are found in the 1985 redesigned engine. However, even the 1979 replacement version showed significant improvement in that a production version would cost only 86 percent of the metal baseline and would weigh 86 Kg (190 pounds) less, in the engine size studied, which would provide a decrease of 0.25 percent in the DOC and a fuel savings of 0.56 percent.

   In considering the fan rotor assembly, composite fan blades were considered practical only for the redesign configurations. In these applications only the blades were composite with the metal disk weight being adjusted to match the lighter blade weight. This resulted in a fan rotor overall weight reduction of between 24 percent and 30 percent (39 percent on the blades themselves without including the metal disk) and a cost savings of

1. (continued)

from 58 percent to 72 percent of the metal baselines. Again, scaled to a common engine size, this represents a weight savings of from 44 Kg (97 pounds) for the 1979 redesigned fan to 54 Kg (120 pounds) for the 1985 fan rotor assembly. This produced a reduction in DOC of from 0.70 percent to 0.98 percent and a fuel savings of from 0.29 percent to 0.36 percent.

2. Another component that showed significant potential benefit, especially in the area of fabrication cost, was the nacelle. The unitized methods of construction, commonly used for large composite parts, lend themselves especially well to this component and offer very worthwhile improvements in the cost of acoustically treated nacelles. The production cost of a nacelle for the 1985 composite engine is estimated to be only 48 percent of the cost of an equivalent metal structure. The composite redesign version of this nacelle showed a reduction in DOC of 2.23 percent, an increase in ROI of 1.53 percent, and a reduction in fuel used of 1.61 percent. If the composite containment of composite blades is not included as part of the benefit of this nacelle, the reduction in DOC due to the composite nacelle is 1.94 percent, the increase in ROI is 1.39 percent and the fuel saved is 1.15 percent. From this, it is apparent that the use of composite containment for composite blades is in itself a significant item and would become even more so in larger thrust class engines. It should also be pointed out that the required composite containment weight used in this program was probably very conservative (possibly by as much as a factor of 3) due to a lack of actual test data.

   The weight savings ranged from 19 percent to 25 percent depending on the concept. Scaled to a common engine size, this represents a savings of from 191 Kg (421 pounds) for the 1985 replacement nacelle to 275 Kg (605 pounds) for the 1979 redesigned nacelle. These numbers include the appropriate containment weights. Again, as in the fan frame, the lesser weight savings for the 1985 engine is a reflection of the estimation of the advanced metal designs assumed to be available for that time period.

3. Other components investigated in the cool part of the engine, although showing some savings in weight and cost did not show sufficient payoff in DOC, ROI, or fuel saved to be included in individual development programs. These items were the stator case assembly, spinner, and booster blades and could later be incorporated using technology obtained from the development of the more significant components.

4. Metallic composites showed very little payoff in the compressor and fan components. The primary reason is that for subsonic high bypass turbofans the application is limited because the front end is relatively cool and polymeric composites can be used at a lower cost and weight.

5. The concept of replacing an existing metal component with a composite component which must mate with an existing structure, while still showing a definite improvement, is not nearly as efficient as employing composites in the original engine/nacelle design.

6. Although much concern has been expressed about the maintenance aspects of composite structures, no significant problems exist with the majority of the composite components currently in use that could not be alleviated with proper attention to detail during the design phases.

7. The results of the study showed that the most significant effect of the use of advanced turbine blade materials is in the reduction in required cooling air and the resultant increase in engine efficiency and consequent reduction in fuel consumption. The cost of the advanced turbine blade material must be kept within reason in order to obtain a net improvement in DOC or ROI. Limiting the cost of casing or lay-up of the blade to four times the casting cost of current blade plus material should be a minimum objective. Depending upon the limitations of other engine parts, however, it may prove economical to go to the advanced turbine material in spite of its higher cost to achieve the required thrust.

5.0 RECOMMENDATIONS

Based on the information developed by this study, the following recommendations are made:

1. Even though there is more payoff in a redesigned type of composite application than in a replacement concept, there is still significant advantages to be obtained by the latter approach. In addition to demonstrating the predicted cost and weight payoffs, a replacement design would develop much of the technology required for future new designs and the component could be flight and service tested at a much earlier date than would be the case if a major engine design or redesign were involved.

2. A program should be established which will lead to major metal components of an existing turbofan engine being replaced by composite components. This program should include all the required development effort and should lead to a flight evaluation. The most logical of the high payoff components to use for this type of program would be the fan frame and the fan blades.

3. Development of eutectics and tungsten wire superalloys for turbine blade applications should be continued to better define their potential capabilities and future production costs.

4. An extensive study should be made of the maintenance aspects of major composite structures. This should include an evaluation of the existing repair facilities and of any additions which may be required to handle a large volume of composite structures. This study should also include an evaluation of possible field inspection techniques and of acceptable repair procedures. The types of damage most likely to occur for various engine locations should be identified.

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3. "Economic Impact of Applying Advanced Engine and Airframe Technologies to Transport Aircraft" prepared by General Dynamics and Pratt & Whitney Aircraft Division for NASA, dated August 1973. NASA CR-132268.

4. "Air Transport Association of America Engineering and Maintenance Memorandum" 67-81, 26 October 1967 and 68-4 dated 18 January 1968.

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